Climate Change Reconsidered 11 - 2013

Climate Change Reconsidered ii 2013 IDSO . . . 2013, Idso, Carter, Singer, Ball, Soon, Spencer et al

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published here . . . "for the Sake of Mankind ! "

a Complete "Rebuttal" of the IPCC > Gore > Flannery . . .
on-going "Scare" Campaign- Global Warming / Climate Change !

Climate Change Reconsidered II

Physical Science

Lead Authors/Editors

Craig D. Idso (USA), Robert M. Carter (Australia), S. Fred Singer (USA)

Chapter Lead Authors

Timothy Ball (Canada), Robert M. Carter (Australia), Don Easterbrook (USA), Craig D. Idso (USA), Sherwood Idso (USA), Madhav Khandekar (Canada), William Kininmonth (Australia), Willem de Lange (New Zealand), Sebastian Lüning (Germany), Anthony Lupo (USA), Cliff Ollier (Australia), Willie Soon (USA)

Contributing Authors

J. Scott Armstrong (USA), Joseph D'Aleo (USA), Don Easterbrook (USA), Kesten Green (Australia), Ross McKitrick (Canada), Cliff Ollier (Australia), Tom Segalstad (Norway), S. Fred Singer (USA), Roy Spencer (USA)

Chapter Reviewers

Habibullo Abdussamatov (Russia), Joe Bastardi (USA), Franco Battaglia (Italy), David Bowen (UK), Roy Clark (USA), Vincent Courtillot (France), Christopher Essex (Canada), David Evans (Australia), Sören Floderus (Denmark), Stewart Franks (Australia), Eigil Friis-Christensen (Denmark), Fred Goldberg (Sweden), Larry Gould (USA), William Gray (USA), Vincent Richard Gray (New Zealand), Howard Hayden (USA), Martin Hovland (Norway), Olavi Kärner (Estonia), James O'Brien (USA), Garth Paltridge (Australia), Donald Rapp (USA), Carl Ribbing (Sweden), Nicola Scafetta (USA), John Shade (UK), Gary Sharp (USA), Jan-Erik Solheim (Norway), Antón Uriarte Cantolla (Spain), Gerd Weber (Germany)

Editors

S.T. Karnick (USA), Diane Carol Bast (USA)

Published for the Nongovernmental International Panel on Climate Change (NIPCC)

The Heartland INSTITUTE

Reviews of *Climate Change Reconsidered II: Physical Science*

"I fully support the efforts of the Nongovernmental International Panel on Climate Change (NIPCC) and publication of its latest report, *Climate Change Reconsidered II: Physical Science,* to help the general public to understand the reality of global climate change."

Kumar Raina, Former Deputy Director General
Geological Survey of India

"*Climate Change Reconsidered II* fulfills an important role in countering the IPCC part by part, highlighting crucial things they ignore such as the Little Ice Age and the recovery (warming) which began in 1800–1850. Superimposed on that recovery, there is a prominent multi-decadal oscillation. These can explain much of climate change from 1800, including the fact that the warming has halted from 2000, phenomena the IPCC reports do not properly cover. In contrast to the IPCC, which often ignores evidence of past changes, the authors of the NIPCC report recognize that climatology requires studying past changes to infer future changes."

Syun-Ichi Akasofu
Founding Director & Professor of Physics Emeritus
International Arctic Research Center, University of Alaska Fairbanks

"The work of the NIPCC to present the evidence for natural climate warming and climate change is an essential counter-balance to the biased reporting of the IPCC. They have brought to focus a range of peer-reviewed publications showing that natural forces have in the past and continue today to dominate the climate signal."

Ian Clark, Department of Earth Sciences
University of Ottawa, Canada

"The CCR-II report correctly explains that most of the reports on global warming and its impacts on sea-level rise, ice melts, glacial retreats, impact on crop production, extreme weather events, rainfall changes, etc. have not properly considered factors such as physical impacts of human activities, natural variability in climate, lopsided models used in the prediction of production estimates, etc. There is a need to look into these phenomena at local and regional scales before sensationalization of global warming-related studies."

S. Jeevananda Reddy, Former Chief Technical Advisor
United Nations World Meteorological Organization

"Library shelves are cluttered with books on global warming. The problem is identifying which ones are worth reading. The NIPCC's CCR-II report is one of these. Its coverage of the topic is comprehensive without being superficial. It sorts through conflicting claims made by scientists and highlights mounting evidence that climate sensitivity to carbon dioxide increase is lower than climate models have until now assumed."

Chris de Freitas, School of Environment
The University of Auckland, New Zealand

"Rather than coming from a pre-determined politicized position that is typical of the IPCC, the NIPCC constrains itself to the scientific process so as to provide objective information. If we (scientists) are honest, we understand that the study of atmospheric processes/dynamics is in its infancy. Consequently, the work of the NIPCC and its most recent report is very important."

Bruce Borders, Professor of Forest Biometrics
Warnell School of Forestry and Natural Resources, University of Georgia

"I support [the work of the NIPCC] because I am convinced that the whole field of climate and climate change urgently needs an open debate between several 'schools of thought,' in science as well as other disciplines, many of which jumped on the IPCC bandwagon far too readily. Climate, and even more so impacts and responses, are far too complex and important to be left to an official body like the IPCC."

Sonja A. Boehmer-Christiansen
Reader Emeritus, Department of Geography, Hull University
Editor, *Energy & Environment*

Climate Change Reconsidered II

Physical Science

Published by THE HEARTLAND INSTITUTE
One South Wacker Drive #2740
Chicago, Illinois 60606 U.S.A.
phone +1 (312) 377-4000
fax +1 (312) 377-5000
www.heartland.org

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11-50 copies	$123 per copy
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Foreword

The Heartland Institute is pleased to partner once again with the Center for the Study of Carbon Dioxide and Global Change and the Science and Environmental Policy Project to produce an authoritative and independent assessment of the latest science concerning the causes and consequences of climate change.

Many scientists, policymakers, and engaged citizens are concerned over the possibility that man-made greenhouse gas emissions, in particular carbon dioxide (CO2), may be causing dangerous climate change. A primary reason for this public alarm is a series of reports issued by the United Nations' Intergovernmental Panel on Climate Change (IPCC). The IPCC claims to know, with apparent rising certainty over time, that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007, p. 10). Is this conclusion based on sound science?

Climate change is a controversial topic because it is interdisciplinary: scientists and experts in widely divergent fields of study can rightfully weigh in on the debate with their insights and informed opinions. A historian of the global warming debate recently observed that "economists should be in a better position than others to make their own assessment of the science because much of it is about statistics and modeling" (Darwall, 2013, p. 239). He quotes Canadian economist Ross McKitrick as saying "the typical economist has way more training in data analysis than a typical climatologist," and "once they start reading climate papers they start spotting errors all over the place." Of course, economists also have their own blind spots.

What is necessary, and too seldom takes place, is a respectful debate on the causes and consequences of climate change in which ideas and theories rise or fall on their merits rather than their pedigree or influence on public policy. A technique frequently used in industry, government, and law when dealing with complex or controversial matters is to deploy competing Green and Red Teams to pursue alternative approaches (e.g., Sandoz, 2001; Nemeth *et al.,* 2001). A Red Team provides a kind of "defense counsel" to verify and counter arguments mounted by the initial Green Team (the "prosecution") as well as discover and present alternatives the Green Team may have overlooked.

For many years, the Green Team of the IPCC has dominated the global debate over climate change. In 2003, however, at a meeting in Milan, a Red Team started to emerge composed of independent scientists drawn from universities and private institutions around the world. Since 2008 that team, the Nongovernmental International Panel on Climate Change (NIPCC), has been independently evaluating the impacts of rising atmospheric CO_2 concentrations on Earth's biosphere and evaluating forecasts of future climate effects.

NIPCC: A Brief History

The Nongovernmental International Panel on Climate Change, or NIPCC, is an international panel of scientists and scholars who came together to understand the causes and consequences of climate change. NIPCC has no formal attachment to or sponsorship from any government or governmental agency. It is wholly independent of political pressures and influences and therefore is not predisposed to produce politically motivated conclusions or policy recommendations.

NIPCC seeks to objectively analyze and interpret data and facts without conforming to any specific agenda. This organizational structure and purpose stand in contrast to those of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which *is* government-sponsored, politically motivated, and predisposed to believing that climate change is a problem in need of a U.N. solution.

NIPCC traces its beginnings to an informal meeting held in Milan, Italy in 2003 organized by Dr. S. Fred Singer and the Science and Environmental Policy Project (SEPP). The purpose was to produce an independent evaluation of the available scientific evidence on the subject of carbon dioxide-induced global warming in anticipation of the release of the IPCC's Fourth Assessment Report. NIPCC scientists concluded the IPCC was biased with respect to making future projections of climate change, discerning a significant human-induced influence on current and past climatic trends, and evaluating the impacts of potential carbon dioxide-induced environmental changes on Earth's biosphere.

To highlight such deficiencies in the IPCC's report, in 2008 SEPP partnered with The Heartland Institute to produce *Nature, Not Human Activity, Rules the Climate,* a summary of research for policymakers that has been widely distributed and translated into six languages. In 2009, Craig Idso and the Center for the Study of Carbon Dioxide and Global Change joined the original two sponsors to help produce *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*, the first comprehensive alternative to the alarmist reports of the IPCC.

In 2010, a Web site (www.nipccreport.org) was created to highlight scientific studies NIPCC scientists believed would likely be downplayed or ignored by the IPCC during preparation of its next assessment report. In 2011, the three sponsoring organizations along with a new co-author, Australian marine geologist Robert M. Carter, produced *Climate Change Reconsidered: The 2011 Interim Report of the Nongovernmental International Panel on Climate Change (NIPCC)*, a review and analysis of new research released since the 2009 report or overlooked by the authors of that report.

In 2013, the Information Center for Global Change Studies, a division of the Chinese Academy of Sciences, translated and published an abridged edition of the 2009 and 2011 NIPCC reports in a single volume. On June 15, the Chinese Academy of Sciences organized a NIPCC Workshop in Beijing to allow the NIPCC principal authors to present summaries of their conclusions.

For all its reports, NIPCC has worked with leading thinkers in the fields of statistics, physics, economics, geology, climatology, and biology. It has avoided the appeals to authority, assumptions, and circumstantial evidence that characterize the reports of the IPCC and other partisans in this debate. The result is a contribution to the debate that reveals some inconvenient truths based squarely on the best available research on climate.

CCR II: Physical Science

Climate Change Reconsidered II: Physical Science is NIPCC's latest report. Lead authors Craig D. Idso, Robert M. Carter, and S. Fred Singer have worked with a team of nearly 50 scientists to produce a report that is comprehensive, objective, and faithful to the scientific method. Despite its heft, it is only the first of two volumes that together mirror and rebut the IPCC's Working Group 1 and Working Group 2 reports. The second volume of *CCR II,* planned for release in 2014, will address impacts, adaptation, and vulnerabilities.

Like the IPCC's reports, NIPCC's reports cite thousands of articles appearing in peer-reviewed science journals relevant to the subject of human-induced climate change. NIPCC presents its findings in seven chapters:

Global Climate Models
Forcings and Feedbacks
Solar Forcing of Climate
Observations: Temperature Records
Observations: The Cryosphere
Observations: The Hydrosphere and Oceans
Observations: Extreme Weather

In keeping with its Red Team mission, NIPCC authors paid special attention to contributions that were either overlooked by the IPCC or that contain data, discussion, or implications arguing against the IPCC's claim that dangerous global warming is resulting, or will result, from human-related greenhouse gas emissions. The Executive Summary beginning on page 1 summarizes NIPCC's principal findings. Most notably, its authors say the IPCC has exaggerated the amount of warming they predict will occur in response to projected increases in atmospheric CO_2, Any such warming that may occur is likely to be modest and will not pose a dangerous threat to the global environment or to human well-being.

Policy Implications

Few scientists deny that human activities can have an effect on local climate or that the sum of such local effects could hypothetically rise to the level of an observable global signal. The key questions to be answered, however, are whether the human global signal is large enough to be properly measured and if it is, does it represent, or is it likely to become, a dangerous change outside the range of natural variability?

NIPCC's conclusion, drawn from its extensive review of the scientific evidence, is that the greenhouse gas-induced global climate signal is so small as to be embedded within the background variability of the natural climate system and is not dangerous. At the same time, global temperature change is occurring, as it always naturally does. A phase of temperature stasis or cooling has succeeded the mild twentieth century warming. It is certain that similar natural climate changes will continue to occur.

In the face of such facts, the most prudent climate policy is to prepare for and adapt to natural climate events and the threats they pose to society regardless of their origin. Adaptive planning for future hazardous climate events and change should be tailored to provide reasonable responses to their known rates, magnitudes, and risks. Once in place, these plans will provide an adequate response to any human-caused change that may or may not emerge.

Policymakers should resist pressure from lobby groups to silence those who question the authority of the IPCC as the sole gatekeeper and voice speaking in behalf of "climate science." *Climate Change Reconsidered II: Physical Science* reveals a scientific community deeply uncertain about the reliability of the IPCC's computer models, its postulates, and its interpretation of circumstantial evidence. This criticism doesn't come from a "fringe" group of the climate science community: It is stated plainly and repeated in thousands of articles in the peer-reviewed literature.

The distinguished British biologist Conrad Waddington wrote in 1941,

> It is … important that scientists must be ready for their pet theories to turn out to be wrong. Science as a whole certainly cannot allow its judgment about facts to be distorted by ideas of what ought to be true, or what one may hope to be true (Waddington, 1941).

This prescient statement merits careful examination by those who continue to assert the fashionable belief, in the face of strong empirical evidence to the contrary, that human CO_2 emissions are going to cause dangerous global warming.

Acknowledgements

As we did in the forewords of previous volumes in the *Climate Change Reconsidered* series, we extend our thanks and appreciation to the many scientists and other experts who helped write this report and its precursors, and to those who conducted the original research that is summarized and cited.

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Diane Carol Bast
Executive Editor
The Heartland Institute

S.T. Karnick
Research Director
The Heartland Institute

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Preface

This report is the result of collaboration among three organizations: Center for the Study of Carbon Dioxide and Global Change, Science & Environmental Policy Project, and The Heartland Institute. Three lead authors -- Craig D. Idso, Robert M. Carter, and S. Fred Singer – assembled and worked closely with nearly 50 chapter lead authors, contributors, and reviewers from 15 countries. This volume was subjected to the common standards of peer-review. Reviewers who agreed to be identified are listed on the title page.

The material presented in this volume builds on three prior NIPCC reports, *Nature, Not Human Activity, Controls the Climate* (Singer, 2008), *Climate Change Reconsidered: The 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)* (Idso and Singer, 2009), and *Climate Change Reconsidered: The 2011 Interim Report of the Nongovernmental International Panel on Climate Change* (Idso, Carter, and Singer, 2011).

Like its predecessor reports, this volume provides the scientific balance that is missing from the overly alarmist reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which are highly selective in their review of climate science and controversial with regard to their projections of future climate change. Although the IPCC claims to be unbiased and to have based its assessment on the best available science, we have found this to not be the case. In many instances conclusions have been seriously exaggerated, relevant facts have been distorted, and key scientific studies have been ignored.

A careful reading of the chapters below reveals *thousands* of peer-reviewed scientific journal articles that do not support, and indeed often contradict, the IPCC's alarmist perspective on climate change. This is not an exercise in "cherry picking": There are simply too many articles by too many prominent scientists, reporting too much real-world data and not merely opinions. Either the IPCC purposely ignores these articles because they run counter to their predetermined thesis that man is causing a climatic crisis, or the IPCC's authors are incompetent and failed to conduct a proper scientific investigation. Either way, the IPCC is misleading the scientific community, policymakers, and the general public by telling only half the story about the science of climate change.

If the IPCC truly considered and acknowledged *all* pertinent science in its assessment reports, there would be no need for a NIPCC. Until such time as the IPCC changes its ways (or is dissolved), NIPCC will continue to inject balance into the scientific debate by finding and reporting the scientific research that the IPCC overlooks. Much of it deals with natural climate processes or variability, weaknesses in climate models and data sets used to measure temperatures or forecast future climate conditions, or with data that raise serious scientific questions about the IPCC's attribution of climate change to human greenhouse gas emissions. Our sole goal in presenting this information is to enable fellow scientists, elected officials, educators, and the general public to make up their own minds about what the science says, to *understand* climate change rather than simply *believe* in it.

Each of the seven chapters in this volume begins with a list of key findings that contradict those of the IPCC. These findings are then discussed in detail using in-depth reviews and analyses of literally thousands of scientific papers. Full citations to the work reviewed are presented at the end of each section. Some of the material is repeated from the 2011 Interim Report and from the earlier 2009 Report, though material from the oldest report is highly abridged and mostly consists of supporting references.

NIPCC scientists have worked hard to remain true to the facts in their representations of the cited studies. Quotations from the original authors are frequently used in discussing their findings and the significance of their work, while editorial commentary in each chapter section is generally limited to an initial introduction and/or conclusion.

Not every scientist whose work we cite is skeptical of the IPCC positions. In fact, there may be many among the thousands we quote who fully embrace the IPCC's claims and projections who may be bothered to see their work quoted in a book written by "skeptics." In scientific research and writing, this is not unusual and is even to be expected. Climate change is a complex topic spanning many disciplines. Climatology as a field is young and new discoveries are being made seemingly every day that reveal how little we actually know about how the climate works. So an expert in one field may not understand or follow the latest developments in another field, and depends on an organization like the IPCC to report accurately and truthfully on the overall picture of the human impact on climate. One important finding from our work is that the IPCC has abused that trust and misled countless scientists and policymakers.

A related but different matter is that some of the authors whose papers we cite may not agree with our interpretation of their work. We are not infallible, so it may be the case that honest mistakes were made. More common, though, are instances noted in the text where we point out that an author's actual findings disagree with the opinions he or she express in introductions and conclusions. By providing ample quotations from the actual findings, we think readers can make up their own minds about who is right.

Finally, we acknowledge that none of NIPCC's scientists knows the truth of all matters related to the global change debate, nor can we say with certainty that this volume doesn't contain a mistake or two in our interpretations of the available evidence. Understanding climate change involves research in many branches of science across a multitude of spatial and temporal scales. We lay no claim to any special source of knowledge that is not available to anyone else on the planet, nor do we pretend to possess superlative powers of discernment. We just look at the data like everyone else does (or should) and then do our level best to decide what they mean. The fruits of that labor are contained in the NIPCC reports we produce, including the present volume.

We wish to thank all those who participated in the writing, reviewing, editing, and proofing of this volume. Our sincere hope is that this report will mark a return to a more balanced and factually-driven analysis of an issue that is in desperate need of much fuller and open discussion, and that it will help policymakers and politicians make rational decisions on climate and energy policy based on *all* the pertinent science, not just the one-sided narrative produced by the IPCC.

Craig D. Idso, Ph.D.
Chairman, Center for the Study of Carbon Dioxide and Global Change

Robert M. Carter, Ph.D.
Emeritus Fellow
Institute of Public Affairs
Australia

S. Fred Singer, Ph.D.
President
Science and Environmental Policy Project

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Executive Summary

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This work provides the scientific balance that is missing from the overly alarmist reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC), which are highly selective in their review of climate science and controversial with regard to their projections of future climate change. Although the IPCC claims to be unbiased and to have based its assessment on the best available science, we have found this to not be the case. In many instances conclusions have been seriously exaggerated, relevant facts have been distorted, and key scientific studies have been ignored.

In keeping with its "Red Team" mission, NIPCC authors paid special attention to contributions that were either overlooked by the IPCC or that contain data, discussion, or implications arguing against the IPCC's claim that dangerous global warming is resulting, or will result, from human-related greenhouse gas emissions. Most notably, its authors say the IPCC has exaggerated the amount of warming they predict to occur in response to future increases in atmospheric CO_2. Any warming that may occur is likely to be modest and cause no net harm to the global environment or to human well-being.

Key Findings by Chapter

Chapter 1. Global Climate Models and Their Limitations

- Properties inherent in models make dynamic predictability impossible. Without dynamic predictability, other techniques must be used to simulate climate. Such techniques introduce biases of varying magnitude into model projections.

- To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes involved in determining climate, but also all important chemical and biological processes that influence climate over long time periods. Several of these important processes are either missing or inadequately represented in today's state-of-the-art climate models.

- Limitations in computing power frequently result in the inability of models to resolve important climate processes. Low-resolution models fail to capture many important phenomena of regional and lesser scales, such as clouds; downscaling to higher-resolution models introduces boundary interactions that can contaminate the modelling area and propagate error.

- The magnitude of the range of projected responses to a doubling of atmospheric CO_2 by itself establishes that large errors and limitations in the models remain to be corrected.

- Many GCMs fail to account properly for certain "multiplier effects" that may significantly amplify the initial impacts of various biospheric processes.

For example, although the absolute variations associated with some solar-related phenomena are rather small, Several multiplier effects may significantly amplify the initial perturbation.

- Major imperfections in the models prevent proper simulation of important elements of the climate system, including pressure, wind, clouds, temperature, precipitation, ocean currents, sea ice, permafrost, etc. Large differences between model predictions and observations frequently exist when comparing these elements or features. In some cases computer models fail to simulate even the correct sign of the observed parameters.

- Although some improvements have been noted in performance between the CMIP3 set of models used in AR4 and the newer CMIP5 models utilized in AR5, many researchers report finding little or no improvement in the CMIP5 model output for several important parameters and features of Earth's climate.

Chapter 2. Forcings and Feedbacks

- Research published in peer-reviewed science journals indicates the model-derived temperature sensitivity of Earth accepted by the IPCC is too large. Negative feedbacks in the climate system reduce that sensitivity to values an order of magnitude smaller.

- Establishing the historic phase relationship between atmospheric carbon dioxide and temperature is a necessary step toward understanding the physical relationship between CO_2 forcing and climate change. When such analyses are conducted, changes in CO_2 are frequently seen to *lag* changes in temperature by several hundred years.

- Many studies reveal a large *uncoupling* of temperature and CO_2 throughout portions of the historical record. Such findings contradict the IPCC's theory that changes in atmospheric CO_2 drive changes in temperature.

- Atmospheric methane observations over the past two decades reside far below the values projected by the IPCC in each of the four *Assessment Reports* it has released to date. The IPCC's temperature projections, which incorporate this inflated influence, should be revised downward to account for this discrepancy.

- Because agriculture accounts for almost half of nitrous oxide (N_2O) emissions in some countries, there is concern that enhanced plant growth due to CO_2 enrichment might increase the amount and warming effect of this greenhouse gas. But field research shows N_2O emissions will likely fall as CO_2 concentrations and temperatures rise, indicating this is actually another negative climate feedback.

- The IPCC has concluded "the net radiative feedback due to all cloud types is likely positive" (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, several studies indicate the net global effect of cloud feedbacks is a cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.

- The IPCC likely underestimates the total cooling effect of aerosols. Studies have found their radiative effect is comparable to or larger than the temperature forcing caused by all the increase in greenhouse gas concentrations recorded since preindustrial times.

- Higher temperatures are known to increase emissions of dimethyl sulfide (DMS) from the world's oceans, which increases the albedo of marine stratus clouds, which has a cooling effect. The IPCC characterizes this chain of events as "a rather weak aerosol-climate feedback at the global scale" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012), but many studies suggest otherwise.

- Several other important negative forcings and feedbacks exist in nature, about which little is known or acknowledged by the IPCC. Such forcings and feedbacks have been shown by multiple scientific studies to significantly influence Earth's climate to a degree comparable to that of projected anthropogenic-induced global warming.

- The IPCC claims a positive feedback exists between climate and the carbon cycle on century to millennial time scales such that a warming climate will result in a loss of carbon storage. There is no empirical evidence to support such an assertion. Just the opposite appears to be the case, as global carbon uptake doubled over the past half-century.

Chapter 3. Solar Forcing of Climate

- Evidence is accruing that changes in Earth's surface temperature are largely driven by variations in solar activity. Examples of solar-controlled climate change epochs include the Medieval Warm Period, Little Ice Age and Early Twentieth Century (1910–1940) Warm Period.
- The Sun may have contributed as much as 66% of the observed twentieth century warming, and perhaps more.
- Strong empirical correlations have been reported from all around the world between solar variability and climate indices including temperature, precipitation, droughts, floods, streamflow, and monsoons.
- IPCC models do not incorporate important solar factors such as fluctuations in magnetic intensity and overestimate the role of human-related CO_2 forcing.
- The IPCC fails to consider the importance of the demonstrated empirical relationship between solar activity, the ingress of galactic cosmic rays, and the formation of low clouds.
- The respective importance of the Sun and CO_2 in forcing Earth climate remains unresolved; current climate models fail to account for a plethora of known Sun-climate connections.
- The recently quiet Sun and extrapolation of solar cycle patterns into the future suggest a planetary cooling may occur over the next few decades.

Chapter 4. Observations: Temperature Records

- The warming of the late-twentieth-century as well as the cessation of warming that occurred since 1998 fall well within the range of natural climate variability.
- Surface-based temperature histories of the globe contain a significant warming bias introduced by insufficient corrections for the non-greenhouse-gas-induced urban heat island effect. Filtering out urbanization and related land-use effects in the temperature record is a complicated task, and there is solid evidence the methods currently used are inadequate.
- Although all greenhouse models show an increasing warming trend with altitude, peaking around 10 km at roughly two times the surface value, the temperature data from balloons give the opposite result: no increasing warming, but rather a slight cooling with altitude in the tropical zone.
- The IPCC claim of robust evidence of amplified CO_2-induced warming in Earth's polar regions is false, having been invalidated time and again by real-world data.
- Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration, revealing the true inability of carbon dioxide to drive climate change throughout the Holocene. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades and centuries even though the atmosphere's CO_2 concentration remained at values approximately 30% lower than those of today.
- An enormous body of literature clearly demonstrates the IPCC's assessment of the Medieval Climate Anomaly (MCA) is incorrect. The degree of warming and climatic influence during the MCA indeed varied from region to region, and hence its consequences were manifested in a variety of different ways. But that it occurred and was a global phenomenon is certain.

- Computer model simulations have given rise to three claims regarding the influence of global warming on ENSO events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. However, this is generally not what observational data reveal to be the case. In fact, in nearly all historical records it is seen that frequent and strong El Niño activity increases during periods of colder temperatures (e.g., the Little Ice Age) and decreases during warm ones (e.g., Medieval Warm Period, Current Warm Period).

Chapter 5. Observations: The Cryosphere

- Satellite and airborne geophysical datasets used to quantify the global ice budget are short and the methods involved in their infancy, but results to date suggest both the Greenland and Antarctic Ice Caps are close to balance.

- Deep ice cores from Antarctica and Greenland show climate change occurs as both major glacial-interglacial cycles and as shorter decadal and centennial events with high rates of warming and cooling, including abrupt temperature steps.

- Observed changes in temperature, snowfall, ice flow speed, glacial extent, and iceberg calving in both Greenland and Antarctica appear to lie within the limits of natural climate variation.

- Global sea-ice cover remains similar in area to that at the start of satellite observations in 1979, with ice shrinkage in the Arctic Ocean since then being offset by growth around Antarctica.

- During the past 25,000 years (late Pleistocene and Holocene) glaciers around the world have fluctuated broadly in concert with changing climate, at times shrinking to positions and volumes smaller than today.

- This fact notwithstanding, mountain glaciers around the world show a wide variety of responses to local climate variation, and do not respond to global temperature change in a simple, uniform way.

- Tropical mountain glaciers in both South America and Africa have retreated in the past 100 years because of reduced precipitation and increased solar radiation; some glaciers elsewhere also have retreated since the end of the Little Ice Age.

- The data on global glacial history and ice mass balance do not support the claims made by the IPCC that CO_2 emissions are causing most glaciers today to retreat and melt.

- No evidence exists that current changes in Arctic permafrost are other than natural or that methane released by thawing would significantly affect Earth's climate.

- Most of Earth's gas hydrates occur at low saturations and in sediments at such great depths below the seafloor or onshore permafrost that they will barely be affected by warming over even one thousand years.

Chapter 6. Observations: The Hydrosphere and Oceans

The Hydrosphere

- Little evidence exists for an overall increase in global precipitation during the twentieth century independent of natural multidecadal climate rhythmicity.

- Monsoon precipitation did not become more variable or intense during late twentieth century warming; instead, precipitation responded mostly to variations in solar activity.

- South American and Asian monsoons were more active during the cold Little Ice Age and less active during the Medieval Warm Period. Neither global nor local changes in streamflow have been linked to CO_2 emissions.

- The relationship between drought and global warming is weak, since severe droughts occurred during both the Medieval Warm Period and the Little Ice Age.

Oceans

- Knowledge of local sea-level change is vital for coastal management; such change occurs at widely variable rates around the world, typically between about +5 and -5 mm/year.
- Global (eustatic) sea level, knowledge of which has only limited use for coastal management, rose at an average rate of between 1 and 2 mm/year over the past century.
- Satellite altimeter studies of sea-level change indicate rates of global rise since 1993 of over 3 mm/year, but complexities of processing and the infancy of the method precludes viewing this result as secure.
- Rates of global sea-level change vary in decadal and multidecadal ways and show neither recent acceleration nor any simple relationship with increasing CO_2 emissions.
- Pacific coral atolls are not being drowned by extra sea-level rise; rather, atoll shorelines are affected by direct weather and infrequent high tide events, ENSO sea level variations, and impacts of increasing human populations.
- Extra sea-level rise due to heat expansion (thermosteric rise) is also unlikely given that the Argo buoy network shows no significant ocean warming over the past nine years.
- Though the range of natural variation has yet to be fully described, evidence is lacking for any recent changes in global ocean circulation that lie outside natural variation or were forced by human CO_2 emissions.

Chapter 7. Observations: Extreme Weather

- Air temperature variability decreases as mean air temperature rises, on all time scales.
- Therefore the claim that global warming will lead to more extremes of climate and weather, including of temperature itself, seems theoretically unsound; the claim is also unsupported by empirical evidence.
- Although specific regions have experienced significant changes in the intensity or number of extreme events over the twentieth century, for the globe as a whole no relationship exists between such events and global warming over the past 100 years.
- Observations from across the planet demonstrate droughts have not become more extreme or erratic in response to global warming. In most cases, the worst droughts in recorded meteorological history were much milder than droughts that occurred periodically during much colder times.
- There is little or no evidence that precipitation will become more variable and intense in a warming world; indeed, some observations show just the opposite.
- There has been no significant increase in either the frequency or intensity of stormy weather in the modern era.
- Despite the supposedly “unprecedented” warming of the twentieth century, there has been no increase in the intensity or frequency of tropical cyclones globally or in any of the specific ocean basins.

1

Global Climate Models and Their Limitations

Anthony Lupo (USA)

William Kininmonth (Australia)

Contributing: *J. Scott Armstrong (USA), Kesten Green (Australia)*

Key Findings

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Key Findings

The IPCC places great confidence in the ability of global climate models (GCMs) to simulate future climate and attribute observed climate change to anthropogenic emissions of greenhouse gases. They claim the "development of climate models has resulted in more realism in the representation of many quantities and aspects of the climate system," adding, "it is extremely likely that human activities have caused more than half of the observed increase in global average surface temperature since the 1950s" (p. 9 and 10 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012).

This chapter begins with a brief review of the inner workings and limitations of climate models. Climate models are important tools utilized to advance our understanding of current and past climate. They also provide qualitative and quantitative information about potential future climate. But in spite of all their sophistication, they remain merely models. They represent simulations of the real world, constrained by their ability to correctly capture and portray each of the important processes that operate to affect climate. Notwithstanding their complexities, the models remain deficient in many aspects of their portrayal of the climate, which reduces their ability to provide reliable simulations of future climate.

Confidence in a model is further based on the careful evaluation of its performance, in which model output is compared against actual observations. A large portion of this chapter, therefore, is devoted to the evaluation of climate models against real-world climate and other biospheric data. That evaluation, summarized in the findings of numerous peer-reviewed scientific papers described in the different subsections of this chapter, reveals the IPCC is overestimating the ability of current state-of-the-art GCMs to accurately simulate both past and future climate. The IPCC's stated confidence in the models, as presented at the beginning of this chapter, is likely exaggerated. The many and varied model deficiencies discussed in this chapter indicate much work remains to be done before model simulations can be treated with the level of confidence ascribed to them by the IPCC.

The following points summarize the main findings of this chapter:

- Properties inherent in models make dynamic predictability impossible. Without dynamic predictability, other techniques must be used to simulate climate. Such techniques introduce biases of varying magnitude into model projections.

- To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes involved in determining climate, but also all important chemical and biological processes that influence climate over long time periods. Several of these processes are either missing or inadequately represented in today's state-of-the-art climate models.

- Limitations in computing power frequently result in the inability of models to resolve important climate processes. Low-resolution models fail to capture many important phenomena of regional and lesser scales, such as clouds; downscaling to higher-resolution models introduces boundary interactions that can contaminate the modelling area and propagate error.

- The magnitude of the range of projected responses to a doubling of atmospheric CO_2 by itself establishes that large errors and limitations in the models remain to be corrected.

- Many GCMs fail to account properly for certain "multiplier effects" that may significantly amplify the initial impacts of various biospheric processes. For example, although the absolute variations associated with some solar-related phenomena are rather small, Several multiplier effects may significantly amplify the initial perturbation.

- Major imperfections in the models prevent proper simulation of important elements of the climate system, including pressure, wind, clouds, temperature, precipitation, ocean currents, sea ice, permafrost, etc. Large differences between model predictions and observations frequently exist when comparing these elements or features. In some cases computer models fail to simulate even the correct sign of the observed parameters.

- Although some improvements have been noted in performance between the CMIP3 set of models used in AR4 and the newer CMIP5 models utilized in AR5, many researchers report finding little or no improvement in the CMIP5 model output for several important parameters and features of Earth's climate.

Introduction

Global Climate Models (GCMs) have evolved from the Atmospheric General Circulation Models (AGCMs) widely used for daily weather prediction. GCMs have been used for a range of applications, including investigating interactions between processes of the climate system, simulating evolution of the climate system, and providing projections of future climate states under scenarios that might alter the evolution of the climate system. The most widely recognized application is the projection of future climate states under various scenarios of increasing atmospheric carbon dioxide (CO_2).

At the core of a GCM is an AGCM that dynamically simulates the circulation of the atmosphere, including the many processes that regulate energy transport and exchange by and within the atmospheric flow. The basic atmospheric flow is represented by fundamental equations that link the mass distribution and the wind field. These equations are represented on a spherically spatial grid field that has many levels representing the depth of the atmosphere. The flow equations are modified by the representation of processes that occur on a scale *below* that of the grid—including such processes as turbulence, latent heat of condensation in cloud formation, and dynamic heating as solar and infrared radiation interact with atmospheric gases, aerosols, and clouds.

The oceans are at least as important as the atmosphere for the transport of energy. For that reason, the GCM also includes an Ocean General Circulation Model (OGCM) that simulates the circulation of the oceans. The OGCM is vital for climate simulations because the oceans represent a dynamic thermal reservoir that, through energy exchange with the atmosphere, dominates the evolution of the climate system. The specification of the processes that regulate heat, moisture, and momentum exchanges between the ocean and atmosphere is crucial to the integrity of a GCM.

Land surface, and how soil moisture and vegetation type regulate heat, moisture, and momentum with the atmosphere, plays a lesser but nevertheless important role in the simulation of climate. Soil moisture and vegetation respond to local precipitation and affect the exchange of heat, moisture, and momentum with the atmosphere over time. The soil moisture and vegetation (and their regulation of land-atmosphere exchange processes) respond to the climate on the shorter time-scale of weather systems but, due to the varying accumulation of soil moisture, the influence of land surface on climate is on seasonal and interannual time-scales.

Surface ice sheets also have an important role in the evolution of the climate system. Their formation and expansion represent a lowering of the total energy of the climate system as a whole because latent heat is lost as water changes from the liquid to solid phase. Likewise, contraction of surface ice sheets represents an increase in the total energy of the climate system. The representation of heat, moisture, and momentum exchanges between ice surfaces and the atmosphere differs from that of land surfaces or ocean surfaces.

Dominating the climate system and its evolution are the radiation processes that regulate the input and output of energy. The shape of the rotating Earth, its distance from the Sun, and the characteristics of its orbit determine the nature of diurnal (daytime) and seasonal solar heating, including its maximum over the tropics. The shedding of energy by infrared radiation originates from the surface, from aerosols, from clouds, and from greenhouse gases of the atmosphere (CO_2, H_2O, O_3, etc.). The latitudinal spread of infrared loss radiation is less than for solar radiation and results in excess solar radiation being absorbed over the tropics but excess radiation shedding over higher latitudes.

A primary function of the climate system is to transport energy from the tropics to higher latitudes; globally, there is an equilibrium between solar radiation absorption and infrared radiation loss to space. Of course, with such a complex system there is rarely perfect balance. At times, especially during the cycle of seasons, Earth is accumulating radiation energy and warming, whereas at other times it is losing energy and cooling. But the rate of radiation loss varies with temperature and acts as a natural thermostat: when Earth warms, the infrared radiation loss to space increases such that it exceeds the solar input and warming ceases; when Earth cools, the infrared radiation loss to space decreases such that solar radiation exceeds the infrared radiation loss and cooling ceases.

The natural thermostat is more complex than this simple portrayal because different components of the climate system interact with limited bands of the infrared radiation spectrum. In particular, variation in surface characteristics, boundary layer aerosol characteristics, cloud height and distribution, and concentration of individual greenhouse gases can all affect the local infrared radiation loss to space across characteristic wavelengths with none affecting the full spectrum. Variations in each component, while acting on a limited wavelength band, will affect the local magnitude of infrared radiation loss to space. Apart from water vapor concentration these variations are not necessarily temperature-dependent. Thus a change to the internal structure of the climate system for whatever reason will—all else being equal—lead to change in Earth's equilibrium temperature.

Within the AGCM there are many important processes that operate on scales below the resolution of the computational grid (sub-grid scale processes) and regulate local temperature, moisture, and momentum. Perhaps the most important of these is convection.

As described by Riehl and Malkus (1958), it is the "hot towers" of deep tropical convection that distribute the accumulating heat and latent energy of the tropical boundary layer through the troposphere. Correct specification of the mass flows within the cloud mass and its surroundings, including the updrafts and downdrafts, is essential for regulating the Hadley Cell circulation and the availability of tropical energy for transport to higher latitudes. Correct specification of the mass flows is also important if the local impact on temperature, water vapor, and momentum are to be quantified. Correctly specifying the mass flows remains a challenge to modelers.

In general, clouds and their interaction with the climate system are difficult to model. Clouds are an outcome of vertical motion and saturation, but the feedback to the circulation through radiation processes is sensitive. Although cloud fields tend to be regulated by the larger scale circulation, the processes leading to cloud formation and dissipation are operating on scales very much smaller than that of the computation grid, with individual clouds often occupying only a small part of a grid. Thus it is necessary for models to specify the climate interaction of a multitude of differing clouds across a grid space by a single process.

AGCMs are very complex and their output should be examined carefully and cautiously. In the physical sciences, mathematical models are often used to formalize a theory or hypothesis. For example, Newton's famous law of gravity formalized a statement of how objects fall or attract each other under ideal conditions (without wind or friction, for example). Note that in Newton's law "gravity" is undefined and remains undefined. Also, in this theory Newton was able to treat objects such as planets as point masses, a successful but auxiliary assumption. Textbook physics is largely made up of laws based on such idealized situations (point masses, frictionless planes, ideal geometric bodies), and in approximations to ideal situations the models of physics work extremely well.

In the real world, however, inhomogeneity and complexity make the basic laws of physics less reliable. Whereas the breakage of simple rods under strain is easy to model and predict, earthquakes, which are also a breakage problem but occur in a complex setting of heterogeneous rock, are not predictable. Just because laws of physics are used does not mean a process is predictable; the climate prediction problem is not "just physics" as some scientists like to claim. It is also helpful to remember the laws of physics were developed by many rounds of experimentation, but it is not possible to conduct experiments at the scale of the whole Earth.

This means models themselves are being tested, in any study using them, to examine the behavior of a phenomenon. The definition of an atmospheric (climate) model is: a hypothesis [frequently in the form of mathematical statements] that describes the processes physically important to describe the workings of the atmosphere (climate and/or climatic change), that has physical consistency in the model formulation, and the agreement with the observations that serve to 'test' the hypothesis [i.e., the model]. The model is typically approximated for testing the hypothesis, but the model should conform to reality (AMS Glossary, 2000).

Once formulated, any atmospheric or climate model is simply a "box" that represents our best estimate of the workings of the atmosphere or climate. It is our best guess or approximation of the main processes of the system being represented and the mechanisms that link the processes. These models can be as complex or as simple as the model creators make them.

A model can be statistical or dynamic, and here we focus mainly on dynamic models, or what are called general circulation models. In a dynamic model, the system is represented in three dimensions, the characteristics of the system are specified at an initial time, and the system is allowed to evolve with time in accordance with the governing equations and boundary conditions that link essential processes.

An Atmosphere-Ocean General Circulation Model (AOGCM) is composed of seven basic mathematical equations with seven basic variables that describe the instantaneous state of the atmosphere over time. This represents a closed and solvable set of equations that can describe atmospheric motions and processes. The equations represent four basic physical principles; correct theories or models representing atmospheric motions will not violate these basic principles: (1) conservation of mass (dry mass and water mass), (2) conservation of energy, (3) conservation of momentum, and (4) elemental kinetic theory of gases. The equations are sequentially solved across the grid space for each time step such that the time directions of quantities at each grid point are affected by their neighbors according to the governing equations.

Physical processes for which there is no precise formulation, or where the formulation is on a scale below that able to be resolved in the model, are represented within these equations by *parameterizations*. Although generally based on observations and simple statistical relationships, the parameterizations often are no more than educated guesses. Representation of sub-grid scale processes is just one of the problems with models, but more computer programming resources are devoted to it than to the basic equations referred to above.

There are other problems with the models that manifest themselves as "computational error," which with time will eventually cause the system evolution to depart from that of the prototype (e.g., Haltiner and Williams, 1980, Durran, 1999).

First, there simply are not enough data available to establish the initial conditions. For example, weather forecasts are made with data measured twice a day in the United States, but once a day in most other locations on the globe. Also, the highest density of weather information is garnered from stations over land, although data continue to be sparse over uninhabited regions. There are vast areas where the atmosphere is poorly represented or sampled by conventional land-based balloon soundings.

To some extent the data problem is overcome by the use of satellite information that has global coverage, albeit the satellite data differ somewhat from traditional thermometer-based observations. Atmospheric satellite sounding data differ from radiosonde data, and satellite-derived ocean skin temperature differs from ship and buoy observations of ocean surface temperature, to name just two. Differences between the satellite and traditional data need to be reconciled in the establishment of starting conditions and the evaluation of predictions.

Second, many atmospheric processes, such as thunderstorms, occur on space scales much smaller than a model's resolution. Energy exchange processes occurring on scales below the resolution of the model must therefore be approximated, or parameterized at the larger scale, and are therefore no longer mechanistic.

The inability to make the required observations with infinite precision means there is always some degree of measurement error or uncertainty associated with the initial conditions at the commencement of the forecast period. This uncertainty and its impact on the flow evolution can be measured by using differential equations and then making multiple runs of the model with slight variations in initial conditions. The error associated with the initial conditions amplifies into the flow structure and propagates through the system with time where it can render a model's prediction unreliable in as short a time as four days (e.g., Lorenz, 1965).

This is not to imply that increased resolution in the models will fix this problem. In fact, there is some indication that further increasing the resolution will lead to diminishing improvements when examined against the cost, in computer time and budgets, of increasing the resolution.

Third, there is also some difficulty in representing the mathematical processes of the basic equations on the fixed grid space. The resolution of the model means the processes cannot be adequately specified and errors in representing the local gradients are amplified during the forecast period. Numerical finite difference methods are used generally to solve the GCM equations. For some operations there are several types of methods available (e.g., Wicker and Skamarock, 2002), making numerical modeling a matter of choosing the right tool for the job.

GCMs have the added complexity of coupling an ocean model, with its own difficulties of process specification, to an atmospheric model and regulating the energy exchange processes through the system by specified energy constraints. As more processes are introduced into the climate model—such as the energetics of the cryosphere, water storage in soils, and the changing of vegetation patterns—the model becomes considerably more complex and the potential for errors to be generated and to amplify in the output is increased.

All of these problems must be balanced against the amount of data a computer can process and how long it takes to produce a model simulation. Thus even this brief discussion and introduction of computer models demonstrates the skepticism through which the validity of model simulations should be evaluated. Unfortunately, there is little discussion by the IPCC about these problems inherent to the models.

It also is critical to understand the difference between weather forecasting and the generation of climate projections or scenarios. Weather forecasting, in principle, is referred to as an initial value problem. Observational data are gathered, quality-controlled, and rendered to the grid space. This is no small problem because data are gathered from several sources, must be checked for consistency with other data, and then are rendered to the grid space in a manner consistent with our basic understanding and assumptions about atmospheric structure and behavior. The forecasts that evolve from these initial conditions are then constrained by the governing equations. To be useful, the evolution of the atmospheric flow must faithfully render the movement, development, and decay of the weather systems specified in the initial analysis. For weather forecasting models it is the structure and movement of the synoptic scale weather systems that is important. It is not as important to maintain global energy equilibrium over the relatively short prediction period of weather forecast.

How far out in time a useful forecast can be generated depends on the size and rotation rate of a planet, as well as the mixture of gases that make up the atmosphere. Using Earth's atmosphere and dimensions, it is widely accepted that a useful forecast can be made for no more than 10 to 15 days—referred to as the forecasting "wall." Clearly, another strategy is needed in making both long-range weather and climate forecasts.

Climate modeling of the atmosphere also involves a boundary value problem. The climate system responds very quickly (relatively speaking) to changes in the pattern of radiation exchange to and from space and to changes in the pattern of heat and moisture exchange between the underlying surface and the atmosphere. Tectonic movements of the continents, on the other hand, are so slow that the land and ocean distribution is generally treated as a constant. But heat and moisture exchanges with the underlying surface vary significantly with ocean surface temperature distribution and vegetation states. Thus the concept of atmospheric climate can be thought of as a servant dependent on the underlying surface. To complicate matters, scientists are still not completely sure about how the exchange of heat and mass between the atmosphere and ocean (and land) take place.

The veracity of climate forecasts depends not only on the ability of the general circulation equations to reproduce the flow structures but also on the specification of the many sub-grid scale processes that regulate energy, moisture, and momentum exchanges at these scales. Errors in any of these specifications will bias local energy accumulations and become evident as a false trend in the evolution of local climate indices. Many of the sub-grid scale exchanges are functions of local temperature or temperature gradient; locally developing biases will propagate spatially with time.

Thus the main distinction between weather forecast models and climate models is that, in the former, the objective is to specify the individual weather systems and reproduce their travel and decay, together with the development of new systems, over time. For climate models the interest is not in individual weather systems that cannot be replicated beyond about two weeks, but in the subtle changes in energy reservoirs over time, especially warming land surfaces, the ocean surface mixed layer, and cryosphere extent. This difference in objective is very large in principle.

There are two distinct types of climate models. Diagnostic, or equilibrium climate models (ECMs) represent steady-state or unchanging processes with time. The ECM is most commonly solved for climatic means and variations and can employ statistical or dynamical methods, or some combination of these, to generate a future climate.

In the second type of climate model, the Prognostic, changes in variables with time are crucial. The time variation for a given variable is the desired output (i.e., a time series). Thus climatic means and variances are changing and can be calculated and compared over limited time intervals.

Both types of models are employed in the study of climate. Generally, the diagnostic model is simpler and produces numerical output faster. Prognostic models are more complex. Either modeling technique can be utilized to create future climate projections or scenarios.

One way of making a climate model projection is to start with today's conditions in a weather forecast model retooled for climate simulation. Researchers "add" carbon dioxide to replicate the rise in greenhouse gases and then run the model to see what output it produces. This approach would seem to be ideal, except there are several atmosphere-ocean interaction processes acting on multiyear to multidecadal time scales that models have not yet mastered. Examples of these phenomena are the El Niño–Southern Oscillation (ENSO, or El Niño and La

Niña), the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO), and, on longer time scales, the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). The physical workings of these processes are not yet well understood, thus it is not surprising there is difficulty in modeling them. The effect of these cycles on regional and even global climate is not trivial, and failure to understand a phenomenon does not excuse leaving it out of a model, which is often done. Omitting such phenomena subjects the models to additional errors and failure.

In evaluating model reliability, the standard assumption has been to compare model output with observations over a given period of Earth's past climate, e.g. since 1850. Doing so, however, requires subjective adjustments to the model; for example, in order to replicate estimated changing solar intensity and atmospheric aerosol loading. These adjustments create additional sources of uncertainty, as limited data exist in the past and knowledge about internal variability and the role of multidecadal-to-century-scale climate cycles is also restricted.

Perhaps it is in light of such limitations that in Chapter 9 of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) (e.g., IPCC, 2013-I) it is conceded that "climate models provide realistic simulations of the large-scale features in the climate system and reproduce observed historical change with only some fidelity. The climate sensitivity of current models has not changed dramatically from that of models assessed in the AR4, in spite of many improvements to the models' representation of physical processes."

Another strategy in creating model projections is to first allow the climate model to equilibrate; i.e., to find a steady climate state under control conditions and then again under conditions that may exist in the future (e.g., double the CO_2 concentration). Then, one can analyze the differences in equilibrium climates in order to project how the climate of this future time will look. It should be kept in mind that a steady-state climate may not exist in nature.

What about projections that show global temperature may rise by as much as 1^o C to 6^o C by 2100 (e.g., IPCC, 2007-I)? Such projections are based on a strategy in which a model is run many, many times from a particular set of initial conditions followed by slightly altered initial conditions. This is called a model ensemble. Generally, due to many of the problems discussed here and to the nature of the basic equations used in the model, the large range in global temperature projections is a natural result of the ensemble technique. The more times a model is run and the longer the time period of evolution used, the greater the spread in the range of the predicted variable, such as global temperature. This is referred to as sensitivity to initial conditions (SDIC). Such behavior is inherent in any system that displays chaotic characteristics, as does Earth's climate system. Chaos theory is another name for the study of such nonlinear dynamics, which are represented in the raw forms of the basic equations.

The IPCC places great confidence in the ability of GCMs to simulate future climate and attribute observed climate change to anthropogenic emissions of greenhouse gases. It says "climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate … and past climate changes. … There is considerable confidence that Atmosphere-Ocean General Circulation Models (AOGCMs) provide credible quantitative estimates of future climate change, particularly at continental and larger scales" (IPCC, 2007-I, p. 591).

The IPCC's confidence in the models, however, is likely considerably overstated. The magnitude of the range of projected temperature responses to a doubling of atmospheric CO_2 itself suggests there are large errors and limitations in the models that must be overcome. To have any validity in terms of future projections, GCMs must incorporate not only the many physical processes described above but also the chemical and biological processes that influence climate over long time periods. In addition, current computational errors resulting from finite grid resolution must be overcome so as not to introduce growing biases. And as a final step, model output must be compared with and evaluated against real-world observations.

The remainder of this chapter delves further into the complexities and problems inherent to computer modeling of the climate system. Other chapters in this volume serve to evaluate the model projections using real-world data observations.

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1.1 Model Simulation and Forecasting

1.1.1 Methods and Principles

J. Scott Armstrong, a professor at The Wharton School of the University of Pennsylvania and a leading figure in forecasting, has pointed out that forecasting is a scientific discipline built on more than 70 years of empirical research, with its own institute (International Institute of Forecasters, founded in 1981), peer-reviewed journals (*International Journal of Forecasting* and *Journal of Forecasting*), and annual International Symposium on Forecasting. The research on forecasting has been summarized as scientific principles, currently numbering 140, that must be observed in order to make valid and useful forecasts (*Principles of Forecasting: A Handbook for Researchers and Practitioners*, edited by J. Scott Armstrong, Kluwer Academic Publishers, 2001).

When physicists, biologists, and other scientists who are unaware of the rules of forecasting attempt to make climate predictions, their forecasts are at risk of being no more reliable than those made by non-experts, even when they are communicated through complex computer models (Green and Armstrong, 2007). In other words, when faced with forecasts by scientists, even large numbers of very distinguished scientists, one cannot assume the forecasts are scientific. Green and Armstrong cite research by Philip E. Tetlock (2005), a psychologist and now professor at the University of Pennsylvania, who "recruited 288 people whose professions included 'commenting or offering advice on political and economic trends.' He asked them to forecast the probability that various situations would or would not occur, picking areas (geographic and substantive) within and outside their areas of expertise. By 2003, he had accumulated more than 82,000 forecasts. The experts barely, if at all, outperformed non-experts, and neither group did well against simple rules" (Green and Armstrong, 2007). The failure of expert opinion to provide reliable forecasts has been confirmed in scores of empirical studies (Armstrong, 2006; Craig *et al.,* 2002; Cerf and Navasky, 1998; Ascher, 1978) and illustrated in historical examples of wrong forecasts made by leading experts, including such luminaries as Ernest Rutherford and Albert Einstein (Cerf and Navasky, 1998).

In 2007, Armstrong and Kesten C. Green of the Ehrenberg-Bass Institute at the University of South Australia conducted a "forecasting audit" of the IPCC *Fourth Assessment Report* (Green and Armstrong, 2007). The authors' search of the contribution of Working Group I to the IPCC "found no references … to the primary sources of information on forecasting methods" and "the forecasting procedures that were described [in sufficient detail to be evaluated] violated 72 principles. Many of the violations were, by themselves, critical."

Green and Armstrong found the IPCC violated "Principle 1.3 Make sure forecasts are independent of politics." The two authors write, "this principle refers to keeping the forecasting process separate from the planning process. The term 'politics' is used in the broad sense of the exercise of power." Citing David Henderson (2007), a former head of economics and statistics at the Organization for Economic Cooperation and Development (OECD), Green and Armstrong state, "the IPCC process is directed by non-scientists who have policy objectives and who believe that anthropogenic global warming is real and dangerous." They thus conclude:

> The forecasts in the Report were not the outcome of scientific procedures. In effect, they were the opinions of scientists transformed by mathematics and obscured by complex writing. Research on forecasting has shown that experts' predictions are not useful in situations involving uncertainty and complexity. We have been unable to identify any scientific forecasts of global warming. Claims that the Earth will get warmer have no more credence than saying that it will get colder.

Scientists working in fields characterized by complexity and uncertainty are apt to confuse the output of models—which are nothing more than a statement of how the modeler believes a part of the world works—with real-world trends and forecasts (Bryson, 1993). Computer climate modelers frequently fall into this trap and have been severely criticized for failing to notice their models fail to replicate real-world phenomena by many scientists, including Balling (2005), Christy (2005), Essex and McKitrick (2007), Frauenfeld (2005), Michaels (2000, 2005, 2009), Pilkey and Pilkey-Jarvis (2007), Posmentier and Soon (2005), and Spencer (2008).

Canadian science writer Lawrence Solomon (2008) asked many of the world's leading scientists active in fields relevant to climate change for their views on the reliability of computer models used by the IPCC to detect and forecast global warming. Their answers showed a high level of skepticism:

- Prof. Freeman Dyson, professor of physics at the Institute for Advanced Study at Princeton University and one of the world's most eminent physicists, said the models used to justify global warming alarmism are "full of fudge factors" and "do not begin to describe the real world."

- Dr. Zbigniew Jaworowski, chairman of the Scientific Council of the Central Laboratory for Radiological Protection in Warsaw and former chair of the United Nations Scientific Committee on the Effects of Atomic Radiation, a world-renowned expert on the use of ancient ice cores for climate research, said the U.N. "based its global-warming hypothesis on arbitrary assumptions and these assumptions, it is now clear, are false."

- Dr. Richard Lindzen, professor of meteorology at the Massachusetts Institute of Technology and member of the National Research Council Board on Atmospheric Sciences and Climate, said the IPCC is "trumpeting catastrophes that couldn't happen even if the models were right."

- Prof. Hendrik Tennekes, director of research at the Royal Netherlands Meteorological Institute, said "there exists no sound theoretical framework for climate predictability studies" used for global warming forecasts.

- Dr. Richard Tol, principal researcher at the Institute for Environmental Studies at Vrije Universiteit and adjunct professor at the Center for Integrated Study of the Human Dimensions of Global Change at Carnegie Mellon University, said the IPCC's *Fourth Assessment Report* is "preposterous ... alarmist and incompetent."

- Dr. Antonino Zichichi, emeritus professor of physics at the University of Bologna, former president of the European Physical Society, and one of the world's foremost physicists, said global warming models are "incoherent and invalid."

Dyson has written elsewhere, "I have studied the climate models and I know what they can do. The models solve the equations of fluid dynamics, and they do a very good job of describing the fluid motions of the atmosphere and the oceans. They do a very poor job of describing the clouds, the dust, the chemistry, and the biology of fields and farms and forests. They do not begin to describe the real world that we live in" (Dyson, 2007).

Many of the scientists cited above observe computer models can be "tweaked" to reconstruct climate histories after the fact. But this provides no assurance that the new model will do a better job of forecasting future climates, and it points to how unreliable the models are. Individual climate models often have widely differing assumptions about basic climate mechanisms but are then "tweaked" to produce similar forecasts. This is nothing like how real scientific forecasting is done.

Kevin Trenberth, a lead author along with Philip D. Jones of Chapter 3 of the Working Group I contribution to the IPCC's *Fourth Assessment Report*, replied to some of these scathing criticisms on the blog of the science journal *Nature.* He argued "the IPCC does not make forecasts" but "instead proffers 'what if' projections of future climate that correspond to certain emissions scenarios" and then hopes these "projections" will "guide policy and decision makers" (Trenberth, 2007). He says "there are no such predictions [in the IPCC reports] although the projections given by the Intergovernmental Panel on Climate Change (IPCC) are often treated as such. The distinction is important."

This defense is hardly satisfactory. As Green and Armstrong (2007) point out, "the word 'forecast' and its derivatives occurred 37 times, and 'predict' and its derivatives occurred 90 times in the body of Chapter 8 of the Working Group I report, and a survey of climate scientists conducted by those same authors found "most of our respondents (29 of whom were

IPCC authors or reviewers) nominated the IPCC report as the most credible source of forecasts (not 'scenarios' or 'projections') of global average temperature." Green and Armstrong conclude, "the IPCC does provide forecasts."

Green and Armstrong subsequently collaborated with Willie Soon in conducting validation tests of the IPCC forecasts of global warming (Green, Armstrong, and Soon 2009). To do so, they tested whether the warming-trend forecasts used by the IPCC are more accurate than the standard benchmark forecast that there will be no change. They tested the IPCC's "business as usual" 0.03˚C p.a. forecast and the no-change forecast from one to 100 years ahead on a rolling basis over the period of exponentially increasing human CO_2 emissions from 1851 to 1975. The procedure generated 7,550 forecasts from each of the forecasting procedures.

The Green, Armstrong, and Soon validation test was a weak one, in that the IPCC forecasts were tested against historical data (HadCRUt3) the IPCC modelers knew exhibited a warming trend. Green, Armstrong, and Soon therefore were surprised to find the errors from the IPCC warming trend forecasts were nearly eight times greater than the errors from the no-change forecasts. For the longer 91 to 100 years-ahead forecast horizons, the IPCC errors were nearly 13 times greater for the 305 forecasts. The no-change forecasts were so accurate in the validation test that the authors forecast annual global mean temperatures will be within 0.5˚C of the 1988 figure for the next 100 years. For public policy and business planning purposes, it is hard to see that any economic benefit could be obtained from forecasts that were less accurate than forecasts from the no-change model. The implication of the Green, Armstrong, and Soon forecasts is that the best policy is to do nothing about global warming. Their findings did not, however, stop the claims that "we are at a turning point" and "it is different this time."

If public policy to address global warming is to be made rationally, it must be based on scientific forecasts of (1) substantial global warming, the effects of which are (2) on balance seriously harmful, and for which (3) cost-effective policies can be implemented. Armstrong, Green, and Soon (2011) refer to these logical requirements of policymaking as "the 3-legged stool" of global warming policy. A failure of any leg would invalidate policies. To date, there are no evidence-based forecasts to support any of the legs.

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1.1.2 Computational Issues

To commemorate the publication of the 100th volume of the journal *Climatic Change*, Norman Rosenberg (Rosenberg, 2010) was asked to contribute an overview paper on progress that had occurred since the journal's inception in the interrelated areas of climate change, agriculture, and water resources. Rosenberg accepted and at the age of 80 conducted his review quite admirably.

He began by noting the "overarching concern" of the volumes he edited was "to gain understanding of how climatic change affects agricultural production, unmanaged ecosystems and water resources; how farmers, foresters and water managers can strengthen these sectors against the negative impacts of climatic change and capitalize on positive impacts if any; how they can adapt to impacts that cannot be so modified or ameliorated and how they can contribute directly or indirectly to mitigation of anthropogenic climatic change—as, for example, through soil carbon sequestration and the production of biomass to substitute in part for the fossil fuels that are adding CO_2 to the atmosphere."

Rosenberg writes in his closing paragraph, "it seems difficult to say with assurance that the 'state-of-the-art' in projecting climatic change impacts on agriculture and water resources and unmanaged ecosystems is, today, that much better than it was 30 years ago," noting "the uncertainty and lack of agreement in GCMs is still too great." He reported, "much can and has been learned about possible outcomes," but "for actual planning and policy purposes we are still unable to assure those who need to know that we can forecast where, when and how much agriculture (as well as unmanaged ecosystems and water resources) will be affected by climatic change."

A similarly pessimistic commentary on the state of climate modeling appeared in 2010 in *Nature Reports Climate Change.* Kevin Trenberth, head of the Climate Analysis Section of the National Center for Atmospheric Research in Boulder, Colorado (USA), writes that one of the major objectives of upcoming climate modeling efforts will be to develop "new and better representations of important climate processes and their feedbacks." The new work, Trenberth wrote, should increase "our understanding of factors we previously did not account for ... or even recognize."

In expressing these sentiments, Rosenberg and Trenberth gave voice to the concerns of many scientists who are skeptical of the reliability of GCMs. Such concerns should not be misinterpreted as "denial." Trenberth, at least, would deny being a "skeptic" of the theory of anthropogenic global warming. It is, rather, the humility of true scientists who—attempting to comprehend the complexity of the world of nature and its innermost workings—are well aware of their own limitations and those of all seekers of scientific truths. Although much has been learned, as Rosenberg and Trenberth outline in their respective essays, what is known pales in comparison to what is required "for actual planning and policy purposes," as Rosenberg describes it, or "certainty" as Trenberth puts it.

In contrast, consider a paper that fails to recognize any such problems. Published in the *Proceedings of the National Academy of Sciences of the United States of America* and written by Susan Solomon (a co-chair of the IPCC's 2007 Working Group 1 report for AR4) and three coauthors, it claims to show "climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop" (Solomon *et al.*, 2009). In the virtual world of computer-run climate models, that may be the case, but that may not be true of the real world. Consider, for example, that the discernible climate signal from a major volcanic eruption is lost after only a few years.

In their paper, Solomon *et al*. set forth three criteria they say should be met by the modeled climatic parameters they studied: "(i) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (ii) the phenomen[a] [are] based upon physical principles thought to be well understood, and (iii) projections are available and are broadly robust across models."

Real-world data provide little or no support for the first criterion (as discussed in other chapters of this volume). The global warming of the past few decades was part of a much longer warming trend that began in many places throughout the world a little more than three centuries ago (about 1680) with the dramatic "beginning of the end" of the Little Ice Age (LIA, see Figure 1.1.1), well before there was any significant increase in the air's CO_2 content. This observation suggests a continuation of whatever phenomenon—or combination of phenomena—may have caused the greater initial warming may have caused the lesser final warming, the total effect of which has been to transport Earth from the chilly depths of the Little Ice Age into the relative balminess of the Current Warm Period.

Climate history is discussed in greater detail in Chapter 4, but it is useful to note here that Earth's current temperature is no higher now (and may be slightly less) than it was during the peak warmth of the Medieval Warm Period (MWP), when there was more than 100 ppm less CO_2 in the atmosphere there is today. Consequently, since the great MWP-to-LIA cooling phase occurred without any significant change in the atmosphere's CO_2 concentration, the opposite could occur just as easily. The planet could warm, and by an equal amount, just as it actually did over the past three centuries without any help from an increase in the atmosphere's CO_2 content.

Regarding the second criterion of Solomon *et al*., studies reported in this volume (see Chapter 2) also show there are non-modeled chemical and biological processes that may be equally as important as the changes in radiation fluxes associated with carbon dioxide employed in the models. The chemical and biological processes are simply not as "well understood" as Solomon *et al.* claim. A highly selective reading of the literature is required to miss the repeated admissions by leading researchers of the uncertainty and outright ignorance of underlying processes that undermine the reliability of GCMs.

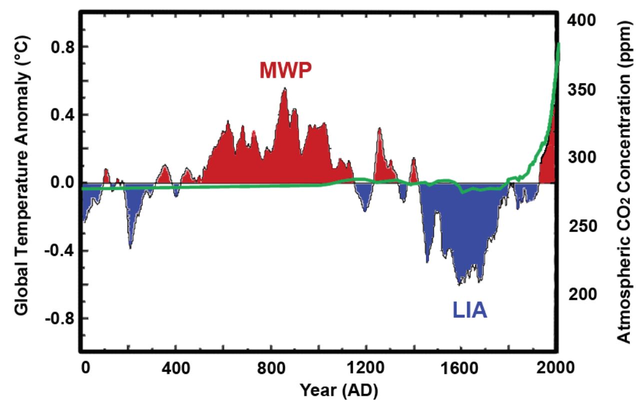

Figure 1.1.1. The mean relative temperature history of the Earth (blue, cool; red, warm) over the past two millennia highlighting the Medieval Warm Period (MWP) and Little Ice Age (LIA), together with a concomitant history of the atmosphere's CO_2 concentration (green). Adapted from Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* **19**: 93–100.

Regarding the third criterion of Solomon *et al.*, many computer model projections are "available and are broadly robust across models." To say such models are "robust" implies they are producing stable climate simulations that are similar to observations. But these models often diverge so greatly in their assumptions and in their specific spatial and temporal projections that they cannot be said to validate each other. Additionally, there is no scientific basis for the often-made claim that an average from such discordant projections can be meaningful. Furthermore, many studies have identified real-world data that contradict what the models say should be occurring.

A good example of an admission of the wide range of uncertainty that undermines GCMs appears in Woollings (2010): "the spread between the projections of different models is particularly large over Europe, leading to a low signal-to-noise ratio. This is the first of two general reasons why European climate change must be considered especially uncertain. The other is the long list of physical processes which are very important for defining European climate in particular, but which are represented poorly in most, if not all, current climate models."

Woollings cited several examples of key atmospheric processes affecting the climate of Europe that models currently do not simulate well, noting (1) the location of the jet stream over northern Europe in most models diverges from reality, (2) zonal flow is biased too far south in most models, (3) the models can't simulate or explain the North Atlantic Oscillation with sufficient magnitude to match historical data, and (4) heat waves and droughts, such as the summer 2010 Moscow heat wave and fires, are caused by blocking, a process the models are currently unable to simulate reliably even in weather forecast models (e.g., Matsueda, 2011), let alone climate models.

In addition, for several key processes the models produce widely varying predictions. The atmospheric circulation response to warming in climate models, for example, is highly variable, as is the change in storm intensity, the projected change in the jet stream, and changes in temperature. It is particularly noteworthy that Europe is predicted to warm less than most Northern Hemisphere sites due to the slowing of the Gulf Stream providing reduced northward heat transport, a factor Woollings noted the models do not simulate well.

It is thus easy to recognize that current climate models are unable to achieve the degree of accuracy necessary in the details of atmospheric circulation that are critical to replicating current weather events, such as droughts, heat waves, and major storms that contribute to the characteristic climate in Europe. Any assertion that frequency or intensity of these events can be forecast 100 years in the future under a changed climate is simply false, and claims about negative impacts of climate change in Europe are based upon no specific modeling skill.

Another problem with climate models is climate drift. Sen Gupta *et al*. (2012) write, "even in the absence of external forcing, climate models often exhibit long-term trends that cannot be attributed to natural variability," and they state "this so-called climate drift arises for various reasons," such as "deficiencies in either the model representation of the real world or the procedure used to initialize the model." They note, however, that "significant efforts by the climate modeling community have gone into reducing climate drift." Nevertheless, they write, "climate drift still persists."

Sen Gupta *et al*. "quantify the size of drift relative to twentieth-century trends in climate models taking part in the Coupled Model Intercomparison Project phase 3 (CMIP3)," which they say "was used to inform the Intergovernmental Panel on Climate Change (IPCC) Forth Assessment Report (AR4)."

According to the seven Australian scientists, their analysis determined that below 1-2 km in the deep ocean, or for depth-integrated properties, drift generally dominates over any forced trend. They report drift in sea level can be large enough to *reverse the sign* of the forced change, "both regionally and in some models for the global average." In addition, because surface drift is spatially heterogeneous, they say "the regional importance of drift for individual models can be much larger than the global figures suggest." As an example, they note "a typical error in calculating a regional forced sea surface temperature trend in the Bjerknes Center for Climate Research Bergen Climate Model, version 2.0 (BCM2.0), CSIRO Mk3.0, and GISS-EH models without accounting for drift would be 30% to 40%." Because this is an average value, still-larger errors would be expected at some locations.

While providing some suggestions for addressing climate modeling drift problems, Sen Gupta *et al*. write, "in the absence of a clear direction forward to alleviate climate drift in the near term, it seems important to keep open the question of flux adjustment within climate models that suffer from considerable drift." They indicate "flux adjustments are nonphysical and therefore inherently undesirable" and "may also fundamentally alter the evolution of a transient climate response," citing the work of Neelin and Dijkstra (1995) and Tziperman (2000).

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1.1.3 Dealing with Chaos

1.1.3.1 Chaotic Systems

The ability of atmosphere-ocean GCMs to predict the climatic effects of human alterations of greenhouse gases and other factors cannot be tested directly with respect to a point in time a hundred years in the future. However, it is still possible to determine whether those models can in principle make such predictions with a reasonable degree of accuracy.

One way to evaluate this ability is to consider the effects of errors in system initial values. If a system is well-behaved, small initial errors will lead to small future errors or even damped responses. In a chaotic system, on the other hand, small initial errors will cause trajectories to diverge over time; for such a system (or model), true predictability is low to nonexistent. This does not mean realistic behavior in the statistical sense cannot be simulated, only that detailed predictability (will it rain 60 days from now, or how much will it rain this year) is impossible.

1.1.3.2 Sensitivity Dependence

One of the characteristics of chaotic systems, such as the fluid we call our atmosphere, is *sensitive dependence on the initial conditions* (SDIC). SDIC means one can take an initial state for our atmosphere, including all the temperature, pressure, and other measurements, and put them into a computer model and generate, for example, a 48-hour weather forecast. If we use an identical model but adjust these initial measurements by small amounts representing error, it is possible to generate a 48-hour forecast much different from the first one.

In weather forecasting, for example, some 15 to 20 model runs are strategically generated in order to examine how much "spread" there is between the multiple runs. If the forecasts show little spread, a weather forecaster can be more confident in the model projections; if there is a great deal of spread, the forecaster must rely on other tools to develop a forecast.

In a study addressing initial value errors, Collins (2002) used the HadCM3 model, the output of which at a given date was used as the initial condition for multiple runs in which slight perturbations of the initial data were used to assess the effect of a lack of perfect starting information, as can often occur in the real world. The results of the various experimental runs were then compared to those of the initial control run, assuming the degree of correlation of the results of each perturbed run with those of the initial run is a measure of predictability.

Collins found "annual mean global temperatures are potentially predictable one year in advance" and "longer time averages are also marginally predictable five to ten years in advance." In the case of ocean basin sea surface temperatures, coarse-scale predictability ranges from one year to several years were found. But for land surface air temperature and precipitation, and for the highly populated northern land regions, Collin concludes, "there is very little sign of any average potential predictability beyond seasonal lead times."

King *et al.* (2010) used an atmospheric GCM to gauge the ability of models to reproduce observed climate trends from the 1960s to the 1990s using model ensembles. They also attempted to quantify the influence of driving factors both internal and external such as sea ice, stratospheric ozone, greenhouse gases, and internal atmospheric variability. Their research was performed using a 100-member ensemble with climatological sea surface temperatures (SSTs) over the globe from 1870 to 2002. Three tests with ten members each were conducted, prescribing SSTs for tropical oceans, for the Indian and Pacific Ocean, and for the tropical Pacific, respectively.

The authors found only when the tropical SSTs were specified were the trends reproduced with a high degree of correlation (correlation = 0.80). The amplitude of these was only about 25 percent that of the observed amplitudes for the ensemble mean. Individual ensemble members were at a maximum of 50 percent of the observed trends. The authors acknowledge "the underestimate of the trend amplitude is a common difficulty even for state-of-the-art AGCMs, as well as coupled models with external forcings." The authors also found Arctic sea ice, CO_2 changes, and stratospheric dynamics and chemistry also contributed to these trends separately and were each major contributors to the decadal variations and trends. None of these forcings separately or together was able to fully represent the observed trends during the 1958–1996 period. None of the ensemble members could reproduce the amplitude of the trends reliably. As stated by the authors, something was missing: "another major player in decadal climate variability is the ocean circulation, which is not accounted for at all by the study here."

A frequent criticism of GCMs is their inability to effectively render past climate. The models used by organizations such as the Intergovernmental Panel on Climate Change are similar to those used in the King *et al*. study above. In King *et al.*'s paper the model performed at its best only when tropical SSTs were included. The authors also cite the need to include ocean dynamics. But even the use of ensemble techniques allowed for only limited success by the models. Clearly, caution should be taken in interpreting future climate scenarios.

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1.1.4 Carbon Dioxide Forcing

The interaction between atmospheric carbon dioxide and Earth's radiation field is at the heart of the anthropogenic climate change debate. In particular, the effect of including in GCMs increasing concentrations of carbon dioxide has been to project global temperature increases that have given rise to additional climate-related concerns about potentially devastating impacts on the biosphere. The alleged possibility of ecosystem extinctions is one example of such concerns that underlie calls to halt carbon dioxide emissions.

There is a long history of scientific debate linking carbon dioxide, through its interaction with Earth's radiation field, to global climate and its variability. The French mathematician Joseph Fourier (1824, 1827) noted Earth should be colder than it is, given its place in the solar system and the strength of solar radiation it absorbs. Fourier's explanation of the apparently abnormal warmth was linked to the insulating properties of Earth's atmosphere. Earth's greenhouse effect was claimed to be an outcome of absorption of radiation emitted from Earth's surface by gases in the atmosphere, which warmed the lower atmosphere and reduced infrared radiation emissions to space.

Credence was given to Fourier's hypothesis via a series of measurements carried out by the English physicist John Tyndall beginning in the late 1850s. Tyndall passed infrared (IR) radiation through different atmospheric gases and measured the absorption. He demonstrated water vapor is a strong absorber of infrared radiation, as is carbon dioxide and some other minor atmospheric constituents.

The Swedish chemist Svante Arrhenius (1896) hypothesized that the shifts of Earth's temperature from glacial to interglacial conditions might be explained by fluctuating changes in the atmospheric concentration of carbon dioxide. In simple terms, when carbon dioxide concentrations are low, there is less absorption of infrared radiation in the atmosphere and temperatures drop. But when concentrations are high, the hypothesis suggests an increased radiative absorption of CO_2 that keeps Earth's temperature warmer. The reason given for the hypothesized fluctuating change in carbon dioxide concentration was varying volcanic activity: When volcanic activity was low, less carbon dioxide was being emitted to the atmosphere than photosynthesis was removing, and atmospheric CO_2 concentration fell; when activity was high, the atmospheric concentration increased.

Arrhenius' hypothesis linking glacial conditions to low carbon dioxide concentrations fell from favour, not because of the links to the greenhouse theory but because it became apparent that recurring glacial events were regular and not explained by volcanic activity. Nevertheless, through the twentieth century the notion that increasing carbon dioxide concentration in the atmosphere would increase global temperature remained an active hypothesis. Systematic measurements of atmospheric carbon dioxide commenced at Mauna Loa Observatory, Hawaii, during the 1957–58 International Geophysical Year. Measurements at other sites have followed to give a global network of CO_2 monitoring and confirm a steadily increasing concentration of atmospheric CO_2. The increase has been attributed to human activity, especially the burning of fossil fuels.

The development of the first GCMs provided an opportunity to test the sensitivity of the climate system to a CO_2 forcing. The first GCMs were rather simple in construction, with the oceans represented as a shallow swamp (Manabe *et al.,* 1965; 1970). Nevertheless, in steady-state the models were able to represent the main features of Earth's climate, including the zonal gradients of temperature and pressure and the main wind systems. Manabe *et al.* (1979) used a similar model to examine the effects of additional carbon dioxide. The GCM was run under conditions of 300 ppm carbon dioxide (1 X CO_2) and 1,200 ppm carbon dioxide (4 X CO_2) and each came to steady-state after about 12 years; the difference in global average surface air temperature between the two concentrations was 4.1°C.

In a general review of carbon dioxide and climate, Manabe (1983) outlined the principles of a simple radiation-convection model that potentially yielded an indicative estimate of the sensitivity of surface temperature to carbon dioxide forcing. First, it was noted earlier surface energy budget models underestimated the sensitivity because of unrealistically large heat and moisture exchanges with the boundary layer, a consequence of the assumption of constant temperature and specific humidity for that layer. An alternative approach was to drive the model by changing the radiative divergence of the atmospheric layers as carbon dioxide concentration increased; net atmospheric radiation loss was offset by vertical convective mixing of heat and moisture from the surface, the surface was assumed to have no heat capacity, and by convective adjustment the tropospheric temperature lapse rate was constrained to no more than the saturated adiabatic lapse rate of 6.5°C/km. Such models consistently returned a surface temperature rise of between 1.5°C and 2.3°C for a doubling of the atmosphere's carbon dioxide concentration.

The Manabe review also outlined contemporary results from GCM forced by doubling of carbon dioxide concentration to a new steady-state. Such models show consistent responses, including: (1) stronger warming over polar regions due to positive feedback as snow and sea ice melt to change surface albedo, (2) amplification of tropical upper tropospheric warming due to the regulation of temperature by convective mixing, and (3) a temperature increase in the Northern Hemisphere greater than that of the Southern Hemisphere. Results from different models, each constructed on similar principles, demonstrated a broader spread in the estimates of climate sensitivity, from 2°C to 3.9°C for a doubling of carbon dioxide concentration.

One characteristic of these early models was the limited impact of the absence of ocean circulation. It was only over the North Atlantic region that temperatures had a cold bias from the lack of ocean heat transport.

On the basis of such computer model findings, an October 1985 U.N.-cosponsored conference in Villach, Austria (Bolin *et. al*., 1985) issued a statement asserting "many important economic and social decisions are being made today on long-term projects … all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century." The statement specifically claimed a doubling of carbon dioxide concentration would lead to a global temperature rise between 1.5°C and 4.5°C. It also asserted the global temperature rise of between 0.3°C and 0.7°C during the twentieth century was consistent with the carbon dioxide increase, implying a cause-and-effect relationship, with CO_2 as the cause.

GCMs have evolved since those early days. Increased computing power has enabled higher spatial resolution both horizontally and vertically. The models also better represent physical processes, couple dynamic ocean and atmospheric circulations, and include a range of bio-geo-chemical processes. Nevertheless, there remain fundamental problems with their representation and treatment of rising carbon dioxide and its potential impact on climate.

Early indicative measures of climate sensitivity were obtained via relatively simple models constrained by three essential assumptions: (1) there is an equilibrium balance between the solar radiation absorbed by the system and the infrared radiation emitted to space, (2) the net radiation loss from the atmosphere (solar and infrared) is offset by heat and latent energy exchange from the surface, and (3) the net radiation excess at the surface (solar and infrared) is offset by the surface-atmosphere heat and latent energy exchange plus heat that goes into surface reservoirs (latent heat melting ice, warming of the land surface, and warming of the ocean).

The concern over climate forcing by increasing the carbon dioxide content of the atmosphere arises because changes in the absorption and emission of infrared radiation by CO_2 in the active wavebands (in the range 12-18μm) vary the intensity of infrared radiation propagating both upwards and downwards throughout the atmosphere, and hence the net radiation transfer from the surface to space. By increasing the concentration of carbon dioxide, the emission to space in the active wavebands emanates from higher in the atmosphere where temperatures are colder. As a consequence, the emission of radiation to space is reduced across the carbon dioxide wavebands. To maintain balance in the overall infrared emission of energy to space it is therefore presumed that global temperatures would rise and increase the emission intensity across non-carbon dioxide wavebands.

As carbon dioxide concentrations increase so too does the intensity of back radiation at the surface across the active wavebands of CO_2, and because this radiation emanates from a lower and warmer layer of the atmosphere, the magnitude of the back radiation increases. Consequently, the net infrared radiation emanating from the surface is reduced, causing a rise in temperature that generates increased heat exchange and evaporation. This surface warming also contributes to an increase in convective instability.

In addition to the reduction in infrared radiation to space and the reduction in net infrared radiation loss from the surface, there is also a reduction in radiation flux divergence (cooling) over the atmosphere, because the former is greater than the latter. The reduction in radiative cooling is effectively a reduction in the rate of generation of convective instability necessary for distribution of heat and latent energy from the surface and through the atmosphere. This is an additional, albeit indirect, factor leading to surface warming, which convectively influences tropospheric temperature.

By convention, the sensitivity of surface temperature to carbon dioxide forcing is expressed as the relationship between the reduction in infrared radiation to space and the increase in surface temperature. However, as described above, the reduction in infrared radiation is confined to the carbon dioxide wavebands. As Earth's climate responds to increasing carbon dioxide, there is no reduction in emission to space, only a shift in the distribution of energy across the infrared spectrum. The shift can be achieved by a general warming (as described in the sensitivity relationship) or by a change in circulation. An enhancement of convective overturning will both expand the area occupied by subtropical subsidence and increase the poleward transport of heat. Enhanced subsidence will dry those regions of the atmosphere, allowing emission to space across the water vapor bands to emanate from a lower and warmer region of the troposphere. Increased poleward transport of heat will warm the middle and high latitude troposphere. Both effects can increase the infrared radiation to space, but neither necessarily leads to warming of the surface.

Held and Sodon (2006) analyzed the set of GCMs used for the IPCC's *Fourth Assessment Report* (Solomon *et al*. 2007) and concluded there was a reduction in overturning as the model Earth warmed with increasing atmospheric carbon dioxide. Their analysis suggests the reason for the reduction in convective overturning was due to the differing rates of increase in atmospheric water vapor increase and surface evaporation as temperature increased. In the models the atmospheric water vapor mass increased according to the Claussius Clapeyron relationship of about 7 percent per degree C (%/C), whereas the surface evaporation increased at only about 2%/C. As atmospheric water vapor increased, the convective clouds processed the water vapor mass flow more efficiently than the rate at which water vapor was being delivered to the boundary layer by surface evaporation. As a consequence, a reduced rate of convective overturning could cope with the marginally more active water cycle.

The convection overturning response identified in the GCMs, however, is in contrast to the tropical observations of Chen *et al.* (2002), who identified a decadal strengthening of the Hadley and Walker Circulations during the warming period of the 1990s. The surface warming generated increased convective instability as reflected in the responses of the two major overturning circulations driven by buoyancy forces.

Analyzing the same GCMs, Richter and Xie (2008) conclude there were three reasons for the rather slow rate of increase in evaporation as temperature increased: (1) an increase in boundary layer stability, (2) a reduction in surface wind speed, and (3) an increase in boundary layer relative humidity. These are surprising findings that suggest in the models, as carbon dioxide concentration increases, the impact on convective instability from reduction in tropospheric radiation cooling overwhelms the increase in convective instability from reduction in net surface infrared radiation loss. The reduction in convective instability is realized as an increase in both boundary layer stability and boundary layer relative humidity, each tending to dampen the rate of increase in evaporation with temperature.

Therefore, after more than four decades of technological evolution in investigating the sensitivity of Earth's climate to increasing carbon dioxide concentration, there remains much uncertainty. The earliest simple surface energy balance models gave very low sensitivity because the reduction in net surface infrared radiation loss as carbon dioxide increased was offset largely by heat and moisture flux that damped surface temperature increase. The more sophisticated radiation/convection models did not discriminate between sensible and latent heat loss and the approximately 2°C temperature rise for doubling of carbon dioxide concentration was considered realistic. Contemporary high-resolution models with a complex representation of physics are even more sensitive to carbon dioxide forcing, but the clear suppression of surface evaporation increase with temperature possibly accounts for the heightened sensitivity.

This history in climate sensitivity makes clear there remain uncertainties with respect to how the interaction between increasing carbon dioxide concentration and Earth's infrared radiation fluxes should be incorporated in complex GCMs. Also key to determining climate sensitivity is the response of the water cycle as the energy exchange processes within the climate system respond. The early simple, albeit flawed, surface energy balance models point to an enhanced water cycle damping the surface temperature sensitivity to carbon dioxide forcing. This unresolved, elemental physics portrayal of the climate system does not lend confidence to current GCM projections under increasing carbon dioxide concentration.

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1.1.5 Climate Sensitivity

The "sensitivity" of temperature to carbon dioxide, which is the amount of total warming for a nominal doubling of atmospheric carbon dioxide, is the core parameter that ultimately drives global warming policy, and its magnitude has been the subject of a vigorous debate between scientists. The current draft of the United Nations' Intergovernmental Panel on

Climate Change AR5 report gives a mean model sensitivity of 3.4°C, and calculations from standard deviation tables given in the draft yield a 90% (5–95%) range of 2.1–4.7°C. As can be seen in Figure 1.1.5.1, these figures are quite high in comparison to a number of prominent recent studies detailed below.

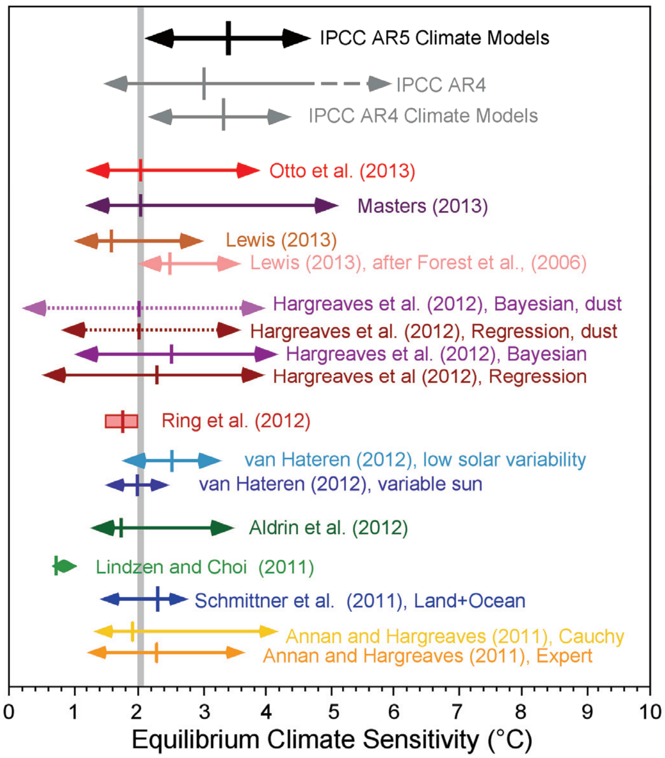

Figure 1.1.5.1. Climate sensitivity estimates from new research published since 2010 (colored, compared with the range given in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (gray) and the IPCC Fifth Assessment Report (AR5; black). The arrows indicate the 5 to 95% confidence bounds for each estimate along with the best estimate (median of each probability density function; or the mean of multiple estimates; colored vertical line). Ring et al. (2012) present four estimates of the climate sensitivity and the red box encompasses those estimates. The right-hand side of the IPCC AR4 range is dotted to indicate that the IPCC does not actually state the value for the upper 95% confidence bound of their estimate and the left-hand arrow only extends to the 10% lower bound as the 5% lower bound is not given. The light grey vertical bar is the mean of the 16 estimates from the new findings. The mean climate sensitivity (3.4°C) of the climate models used in the IPCC AR5 is 13 percent greater than the IPCC's "best estimate" of 3.0°C and 70% greater than the mean of recent estimates (2.0°C).

NASA Senior Scientist David Rind of the Goddard Institute for Space Studies subtitled a recent paper, "We still can't predict future climate responses at low and high latitudes, which constrains our ability to forecast changes in atmospheric dynamics and regional climate" (Rind, 2008). Rind began his review and analysis of this important subject by noting Charney *et al.* (1979) concluded global temperature sensitivity to a doubling of the atmosphere's CO_2 concentration was "between 1.5° and 4.5°C," while noting since then "we have not moved very far from that range." In addition, Rind reported the uncertainty in our assessment of high- and low-latitude climate sensitivity "is also still as great as ever, with a factor of 2 at both high and low latitudes."

Rind identified several problems contributing to the uncertainty. Whether the water vapor response to warming employed by climate models "is realistic is hard to assess," he noted, "because we have not had recent climate changes of the magnitude forecast for the rest of this century" to test against. Closely associated are low-latitude difficulties related to modeling both low- and high-level clouds in the tropics and the physics and dynamics associated with them, plus high-latitude difficulties associated with cryosphere feedbacks related to sea ice and snow cover.

One way of dealing with these uncertainties has been to suggest, in Rind's words, that "we can have greater confidence in the multi-model mean changes than in that of any individual model for climate change assessments." However, he writes, "it is doubtful that averaging different formulations together will end up giving the 'right' result," because "model responses (e.g., tropical land precipitation) can often be of different signs, and there can be little confidence that averaging them together will produce a better result."

Rind thus concludes, "at this point, we cannot determine the low- and high-latitude sensitivities, and we have no real way of obtaining them." These unknowns, in his opinion, "affect the confidence we can have in many of our projections of atmospheric dynamic and hydrologic responses to global warming."

Because of these and a host of other complexities he discusses, Rind states, "forecasting even the large-scale response to climate change is not easy given the current uncertainties" and "regional responses may be the end result of varying influences in part due to warming in different tropical and high-latitude regions."

Rind concludes "real progress will be the result of continued and newer observations along with modeling improvements based on these observations," which observations must provide the basis for evaluating all model implications. So difficult is this task, however, that he says "there is no guarantee that these issues will be resolved before a substantial global warming impact is upon us." There is, of course, also no guarantee there even will be any "substantial global warming impact" from a doubling or more of the air's CO_2 content.

Lindzen and Choi (2009), two Massachusetts Institute of Technology scientists, used the National Centers for Environmental Prediction's 16-year (1985–1999) monthly record of sea surface temperature (SST), together with corresponding radiation data from the Earth Radiation Budget Experiment, to estimate the sign and magnitude of climate feedback over the oceanic portion of the tropics and thus obtain an empirical evaluation of Earth's thermal sensitivity, as opposed to the model-based evaluation employed by the IPCC.

The scientists found all 11 models employed in the IPCC's analysis "agree as to positive feedback," but they all *disagree*—and disagree "very sharply"—with the real-world observations Lindzen and Choi utilized, implying negative feedback actually prevails. Moreover, the presence of that negative feedback reduced the CO_2-induced propensity for warming to the extent that their analysis of the real-world observational data yielded only a mean SST increase "of ~0.5°C for a doubling of CO_2."

Lindzen and Choi (2009) were criticized for not using available tropical high-altitude radiation data and for constraining feedback to within the tropics, which is highly unrealistic for a number of reasons, including Hadley Cell-westerly interactions and the export of large amounts of energy from the tropics into the temperate zone via tropical cyclones and poleward currents. They also did not explicitly use the IPCC-defined climate sensitivity.

However, Lindzen and Choi (2011) addressed these concerns by adding data from NASA's Cloud and Earth Radiant Energy System (CERES), rather than simply using the older Earth Radiation Budget Experiment (ERBE) data. They also shared radiation feedback fluxes with the extratropics and addressed the sensitivity issues. The derived mean sensitivity was 0.7°, with a 90% range of 0.6–1.0°C, indicating virtually no positive amplification of warming beyond that from CO_2.

Another empirically based analysis of climate sensitivity was published several years earlier in the review paper of Idso (1998), who described eight "natural experiments" he personally employed in prior studies designed to determine "how Earth's near-surface air temperature responds to surface radiative perturbations." The eight naturally occurring phenomena employed by Idso were (1) the change in the air's water vapor content that occurs at Phoenix, Arizona, with the advent of the summer monsoon, (2) the naturally occurring vertical redistribution of dust that occurs at Phoenix between summer and winter, (3) the annual cycle of surface air temperature caused by the annual cycle of solar radiation absorption at Earth's surface, (4) the warming effect of the entire atmosphere caused by its mean flux of thermal radiation to the surface of Earth, (5) the annually averaged equator-to-pole air temperature gradient sustained by the annually averaged equator-to-pole gradient of total surface-absorbed radiant energy, (6) the mean surface temperatures of Earth, Mars, and Venus relative to the amounts of CO_2 contained in their respective atmospheres, (7) the paradox of the faint early Sun and its implications for Earth's thermal history, and (8) the greenhouse effect of water vapor over the tropical oceans and its impact on sea surface temperatures.

These eight analyses, Idso writes, suggest "a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration could raise the planet's mean surface air temperature by only about 0.4°C," in line with Lindzen and Choi's deduced warming of ~0.5°C for a nominal doubling of the air's CO_2 content. There would thus appear to be strong real-world data that argue against the order of magnitude larger CO_2 sensitivity predicted by state-of-the-art climate models.

Feedbacks are a natural part of the complexity of our climate system. They represent nonlinear processes within a system that are the result of the interaction between two or more variables or the interaction of a variable with itself (or its changes—"self" interaction) and influence overall climate sensitivity. Generally, these processes can only be parameterized, or represented in the models in an empirical way. Because of the inability to precisely represent feedbacks in a model, the model output may not be reasonable.

Temperature change in the climate system can be represented simply as a "forced-dissipative" relationship, for example by non-radiative and radiative processes as well as a net radiative restoring force, which is the feedback. As an example of this feedback process, if the system warms radiatively or non-radiatively, then the net radiative force may become negative (longwave-out increases and becomes larger than shortwave-in). Thus, the net radiative force will act to counter the warming, and a larger restoring force would represent a less-sensitive climate. The opposite can be argued for the system cooling. These principles can be represented by a simple differential or mathematical equation.

Investigating this subject further, a paper by Spencer and Braswell (2011) explored the sensitivity of the surface temperature response to a forced radiative imbalance. They used observed shortwave and longwave radiation gathered from satellite measurements and calculated the net atmospheric radiation. They also used observed surface temperatures from the years 2000–2010 around the globe and calculated global monthly temperature anomalies relative to the average over the ten-year period. Using these two time series, they correlated one versus the other using different time lags and compared these observed values to the same variables gathered from the twentieth century runs of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) phase 3 multi-model data set. The authors chose the three most- and least-sensitive model runs, rather than using all of them. They also used the observed and modeled data to investigate the mathematical relationship for temperature change described above.

When Spencer and Braswell set a "feedback" parameter as described above, they demonstrated that only for pure non-radiative forcing and with no time lag can the parameter be accurately diagnosed in the model (see Figure 1.1.5.2). With radiative forcing and a 70/30% mix of radiative versus non-radiative forcing, the response was quite different: "in this case, radiative gain precedes, and radiative loss follows a temperature maximum, as would be expected based upon conservation of energy considerations." They also found, more importantly, that the pure radiative forcing curve in Figure 1.1.5.2 looks more like one produced using the data from the climate models, while the mixed curve looks more like that produced using the observed data.

Spencer and Braswell then point out, "we are still faced with a rather large discrepancy in the time-lagged regression coefficients between the radiative signatures displayed in the real climate system in satellite data versus the climate models." Such discrepancy indicates the climate system possesses less sensitivity that the climate models project. That is, climate models may overestimate the temperature change forced by a certain process (e.g., increasing atmospheric CO_2).

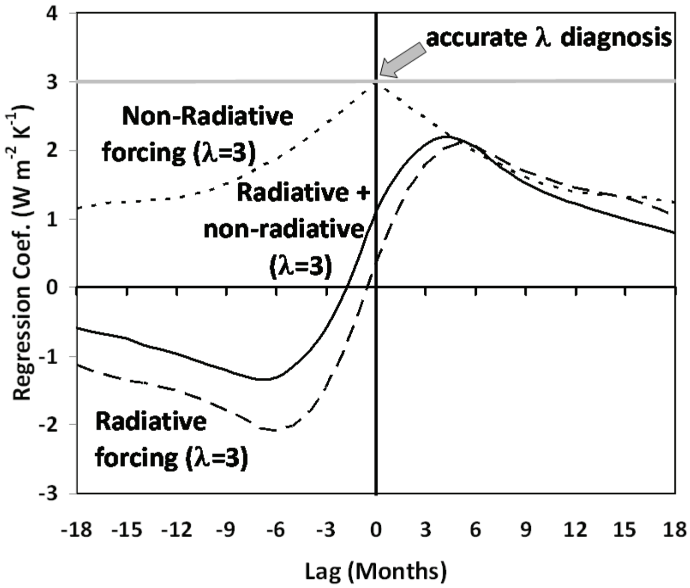

Figure 1.1.5.2. The lag regression coefficients between temperature (K) and radiative flux (W m^{-2} K^{-1}) for the case of (a) non radiative forcing (dotted line), (b) pure radiative forcing (dashed line), and (c) a 70/30% mixture of radiative and non-radiative forcing. Adapted from Spencer, R.W. and Braswell, W.D. 2011. On the misdiagnosis of surface temperature feedbacks from variations in Earth's radiant energy balance. *Remote Sensing* **3**: 1603–1613, Figure 4.

Further, it should be noted Earth's climate is a complicated dynamic system in which each part has characteristic time- and space-scales over which it evolves, or as it reacts to a forcing that is external to that part of system or to the system as a whole. The atmosphere, being less massive than the ocean or the cryosphere, tends to respond more rapidly than the other parts of the system. Thus, when the climate of the atmosphere by itself is modeled, we consider the atmosphere a boundary value problem; the atmosphere will be a servant to the underlying surface. It is often stated that the oceans, with their greater mass and higher thermal capacity, are the inertial and thermal flywheels of the climate system.

A number of recent papers have eliminated the feared "fat tail" of a reasonably finite probability of very large warming and reduced or median estimates.

Annan and Hargreaves (2011) adjusted Bayesian probability estimates of the range of sensitivity based upon analysis of their sensitivity to the choice of prior and recent ERBE data. They determined a sensitivity of 1.2–3.6°C, with a most likely value of 2.2°, which also eliminated the long "long fat tail" they note is "characteristic of all recent estimates of climate sensitivity." A Cauchy-derived probability gave 1.3–4.2°C, with a quite low 1.9° at p=0.5.

Also using a Bayesian approach, Schmittner *et al.* (2011) created an empirical-dynamic combination of land and ocean temperature reconstructions during the last glacial maximum combined with climate model simulations. Both eliminated the "fat tail," with a probability density function (PDF) showing a "vanishing" probability below 1.0°C and above 3.2°C, and a 90% range of from 1.4–2.8°C. What is rather remarkable in this paper is how tightly constrained the PDF becomes when "real world" (interglacial/glacial) data are used, as the 66% range is not much smaller than the 90%, at 1.7–2.6°C, a net range change of only 0.5°C.

Aldrin *et al*. (2011) used a rather simple energy balance model to determine hemispheric surface temperature and global ocean heat content as a function of the estimated changes in radiative forcing. They derived a 90% range of 1.2–3.5°C, with a p=0.5 value of approximately 1.75°. Again using a single-average Earth temperature as the predictand, van Hatteren (2012) calculated an equilibrium sensitivity 90% confidence range of 1.7–2.3°C. Notably, the fit to the observed temperature rise in the past two centuries was significantly worse (and more warming was predicted) when van Hatteren's solar variability parameter was reduced by an order of magnitude.

Ring *et al*. (2012) did not calculate a sensitivity range, but rather estimated equilibrium warming with a spectral decomposition model of the four main global temperature data sets, fit to long-lived greenhouse gases, compensating aerosols, changes in tropospheric ozone and land use, solar irradiance, and volcanic activity in a model estimating land and ocean temperatures, with a 40-layer oceanic model to allow for latitudinal advection of heat. Their equilibrium temperature change ranged from 1.5 to 2.0°C, and they noted

> …. These are on the low end of the estimates in the IPCC's *Fourth Assessment Report*.[1] So, while we find that most of the observed warming is due to human emissions of [long-lived greenhouse gases], future warming based on these estimations will grow more slowly than that under the IPCC's "likely" range of climate sensitivity, from 2.0°C to 4.5°.

Notably, the fourth author of this paper, University of Illinois climate modeler Michael Schlesinger, has been one of the most outspoken advocates of stringent and immediate controls of greenhouse emissions and, in earlier work, he had produced some of the largest estimates of equilibrium warming from carbon dioxide.

Using both posterior (regression) and prior (Bayesian) approaches, Hargreaves *et al*. (2012) calculated the sensitivity with models that either included or excluded atmospheric dust, where these approaches were coupled to seven common General Circulation Models (GCMs). The dust-free Bayesian model had the greatest sensitivity, with a range of 1.0–4.2°, with a central estimate of 2.4°C. The dust-included regression model yielded the smallest warming, a range of 0.8–3.4°C, with a central estimate of 2.0°C. The Bayesian dust-included model had a similar central estimate. Perhaps more important, Hargreaves *et al*. noted their collection of models yielded "a high probability of [equilibrium warming] lying below 4°C."

Again coupling a Bayesian approach to a model, this time the MIT two-dimensional model, Lewis (2013) generated a 90% range of 1.0–3.0°C, with a central value of 1.6°C. Masters (2013) is the only recent sensitivity analysis based upon observed values of oceanic heat uptake, and he found a 90% sensitivity range of 1.2–5.1°, with a central value again of 2.0°C, substantially below what is in the suite of models employed in the existing draft of the IPCC's *Fifth Assessment Report*.

Scaling the relationship between observed temperature in the widely cited HadCRUT4 temperature history with calculated changes in the total heat content of the Earth system, Otto *et al*. (2013) state their most reliable calculation yields a range of 1.2–3.9°C, centered on 2.0°C. The analogous range for the upcoming IPCC report is 2.2–4.7°C, centered on 3.4°C. This paper was authored by17 very prominent climate scientists.

Many of the sensitivity values are very similar to the twenty-first century warming Michaels *et al*. (2002) had projected some ten years earlier based largely on observational data, which may be the first of the low-sensitivity data-based papers in the literature.

In total, there are 42 researchers describing 19 separate experiments in this section.

In another paper, Olivé *et al.* (2012) examined the changes in global temperature relative to changes in CO_2 concentration using two different models. This study also endeavored to quantify the uncertainties in the authors' scenarios. The authors used output from the Hadley Centre's Atmosphere-Ocean (UKMO-

HadCM3) and the CNRM-CM3 Centre National de Recherches Meteorologiques Coupled Model, version 3 (CNRM-CM3) coupled Atmosphere Ocean General Circulation Models (AOGCMs). The simulations were relatively short, on the time scale of 100 to 300 years, since the model spatial resolution was higher. The authors also used CO_2 scenarios where the increase was simulated to be sudden, corresponding to a 6.5 times increase (10 W/m^2), a sudden doubling, and then a gradual increase. The gradual increases (1% per year) resulted in a doubling and quadrupling of CO_2 in 70 and 140 years, respectively. Additionally, the authors initially used a shorter (10 years) and long-scale (100 years) CO_2 forcing as well as sensitivity values within the range of those given in the published literature for their *a priori* estimates. Then they solved the equations backward to get their estimates of the short- and long-time-scale modes and sensitivity.

The results from Olivé *et al*. (2012) show the short-time-scale temperature forcing for CO_2 was on the order of three to four years, while it was 100 to 300 years on the long-time-scale. The shorter mode of temperature change was faster for the model simulations where the CO_2 forcing was sudden (Figure 1.1.5.3) rather than the gradual CO_2 increase simulations. The uncertainty also was lower for the sudden increase simulations. For the longer time-scale forcing, longer model integrations would be needed to estimate these and reduce the uncertainty. Concerning the model sensitivities, the authors write, "when assuming two modes it varies between 0.49 and 0.83 K W^{-1} m^2 or between 0.56 and 1.01 K W^{-1} m^2," both within the published range shown early in the paper.

This kind of diagnostic work is an important use of long-term computer model simulations. Even though there is no predictive work being done in this study, it is remarkable that there is such variation in the estimate of the short- and long-term radiative forcing as well as in the climate sensitivity. This is especially true between the two models used. Such findings demonstrate the models are less than perfect, as any of these internal differences would have to be the result of the model physics employed, especially that pertaining to radiative forcing. Also, such long integrations should lead to the build-up of numerical errors. Lastly, the fact that the authors could not appreciably reduce the uncertainty in estimating these quantities indicates further improvement is not likely using the current technology.

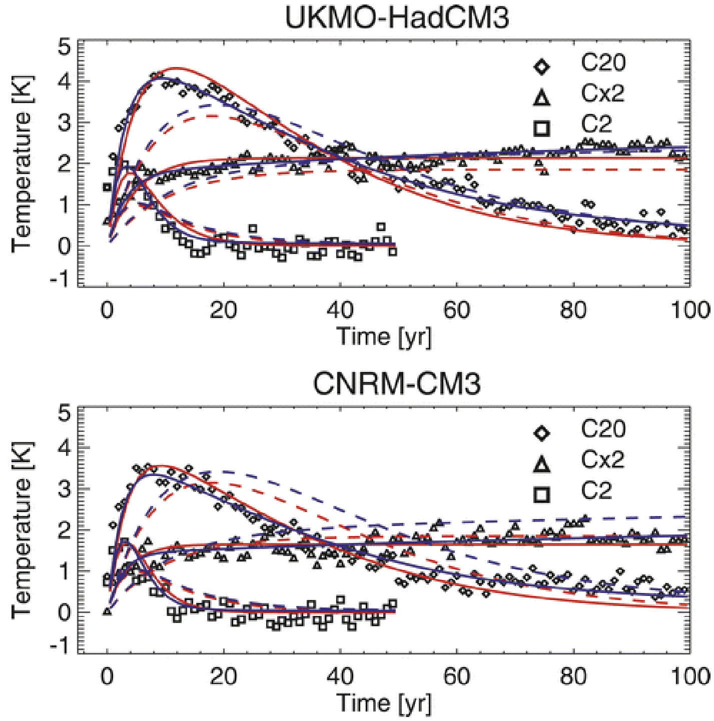

Figure 1.1.5.3. A time series of global- and annual-mean surface air temperature obtained with a one(red line) and two (blue line) mode approach for (top) UKMO-HadCM3 and (bottom) CNRM-CM3. The model data are represented by the symbols, and the modal results obtained using a priori (a posteriori) parameter values are represented by the dashed (solid) lines. C20 and Cx2 represent scenarios with increased atmospheric CO_2 in a stepwise fashion (Cx2 is slower). The C2 scenario represents a sudden doubling of CO_2. Adapted from Olivé, D.J.L., Peters, G.P., and Saint-Martin, D. 2012. Atmosphere Response Time Scales Estimated from AOGCM Experiments. *Journal of Climate* **25**: 7956–7972, Figure 1.

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1.1.6 Climate Response and Projection

Climate change can occur due to internal variations in the system or internal forcing, the interaction among properties or parts of the climate system with each other. Climate also can be forced externally, influenced by phenomena considered to be outside the climate system, such as volcanic action, solar forcing, or an "artificial" disturbance such as that imposed by human-emitted greenhouse gases.

The IPCC used GCMs to make two claims about anthropogenic climate warming. The first is that most or all of the warming occurring during the latter part of the twentieth century was human-induced. In its *Fourth Assessment Report* (AR4), the IPCC asserts anthropogenic forcing dominates natural forcing. Yet even in AR4 (Chapter 2), the IPCC admits low confidence in its knowledge of the size of solar forcing since 1750. By contrast, the Nongovernmental International Panel on Climate Change (NIPCC, 2009) has demonstrated a strong correlation between, for example, solar variations and global temperature (see also Chapter 3 of this volume). The second claim made by the IPCC in AR4 is that by the end of the twenty-first century, a warming of 1.0 °C to 3.6 °C or more will have occurred due to human activity.

The IPCC's assertion of the dominance of anthropogenic forcing is merely that: an assertion. Decades ago, Leith (1975) used the fluctuation-dissipation (F-D) theorem from statistical mechanics to study "the way in which a climate mean would return to its original value after it had been artificially perturbed." In his short paper he proved the theorem mathematically and then applied it to the problem of using climate models to create climate change scenarios. In his proof of the F-D theorem, Leith demonstrated that as long as the conditions for the theorem hold, the mean dissipation of a fluctuation (or disturbance) is that projected by a linear regression (statistical) model. It would not matter whether the disturbance was artificial or natural, just that they be small and of similar size. Leith acknowledged the character of the climate system may not be such that the F-D theorem holds exactly, but studies in turbulence show it is a reasonable approximation for its behavior.

One implication is that it is difficult to ascribe temperature change to one process if two or more processes causing the temperature change are of similar magnitude. Moreover, if it is assumed that an artificial forcing is much greater than a natural forcing, as does the IPCC, then the GCMs will generate climate responses much larger than those of natural variability. Lastly, the F-D theorem implies the use of complex GCMs will not necessarily project future conditions any better than a statistical model.

The fact that observed global temperature increases in the instrumental record since the late 1800s do not show rates of change sufficiently larger, or even different from, those implied in the proxies for the last one to two millennia (Figure 1.1.6.1; see also Chapter 4) does not bode positively for the IPCC's assumption that human forcing is the dominant player in climate change. Even a further warming (of about 0.6°C or less) by 2100, as predicted by the IPCC, does not necessarily imply an anthropogenic origin.

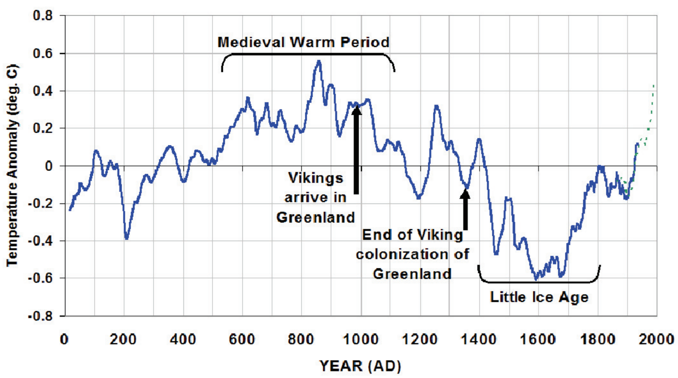

Figure 1.1.6.1. The estimate of global temperature change for the past 2,000 years (2 KY) in degrees centigrade. Adapted from Spencer, R., 2013, http://www.drroyspencer.com/latest-global-temperatures/.

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1.1.7 Regional Projection

Some observers of the climate change debate, scientists and non-scientists alike, have criticized the efforts to model future climate by asking how projections 100 years into the future can be made when a weather model can't get this weekend's weather right. Modeling is a complicated process, and weather forecasting and climate projection are two very different problems that require different strategies.

Weather forecasting can be done dynamically, by (a) taking the mathematics and physics that represent the atmosphere, (b) initializing with a clean set of measurements, and (c) running a computer program forward, generating a forecast that in theory represents the atmosphere at a certain prediction time. However, as noted earlier, such predictions can be calculated for only about 10 to 14 days into the future.

Climate projection (as opposed to weather prediction) relies on the assumption that the statistics generated after lengthy simulations (years or decades) would adequately represent the climate of some future period. The focus of climate projections is to replicate the energy flows within the climate system such that any accumulation or decrease represents real changes due either to internal redistribution of energy or imbalances in the radiation exchange to space.

The basis for confidence in the anthropogenic global warming hypothesis is that changes in atmospheric carbon dioxide concentration introduce a bias in the exchange of radiation energy with space. As the boundary energy exchanges slowly change, there is a concomitant movement of internal indices, such as global surface temperature, that can be modeled. Such projections require additional physics and tighter constraints on the magnitudes of internal energy exchanges than those utilized in weather forecasting models. For example, changing aerosol forcing from natural or human sources would have a negligible effect on the prediction of weekend weather, but over the course of many years can have a large impact on regional or global climate.

In a recent paper, Liang *et al.* (2012) examined the feasibility of converting the Weather Research and Forecasting model (WRF) into a regional climate model (CWRF). In doing so, they noted "there has been some success using the WRF for regional climate downscaling," adding that "such direct applications, however, also have encountered numerous problems."

In order to convert the WRF for climate projections, the authors acknowledged the need for the use of cloud aerosol and radiation physics more common to climate models. Also, atmospheric "communication" with the oceans and land (exchanges of heat, moisture, and momentum) needed to be upgraded to deal with boundary value problems. Additionally, the horizontal and vertical resolutions used were the same as those for weather forecasting, 30 km in the horizontal and 36 vertical levels (although weather forecasting can be done at finer resolutions). The model focused on the United States and adjacent regions, and the authors attempted to replicate the climate of the most recent decades and compared their results to observations and those produced by another climate model.

The CWRF generally improved the simulation of the geographical distribution and seasonal/interannual variability of such quantities as precipitation, surface temperature, and downwelling radiation, although not for all regions and seasons. The authors acknowledge "accurate simulation of precipitation in all seasons and regions remains a challenge for all of the tested models." Nonetheless, this initial test proved successful to the satisfaction of the authors, justifying more testing and release of the model to the public.

The CWRF's performance was not universally superior (see Figure 1.1.7.1). For example, used with different physics packages to project the great Mississippi River Basin flooding of 1993, the CWRF demonstrated limited skill. However, for seasonal rainfall rates, there was enhanced skill when the projections were averaged. While this modeling system represents an improvement over others in some respects and is another tool for modelers to use, climate modeling remains an inexact science far from being able to show us the climate of some distant future.

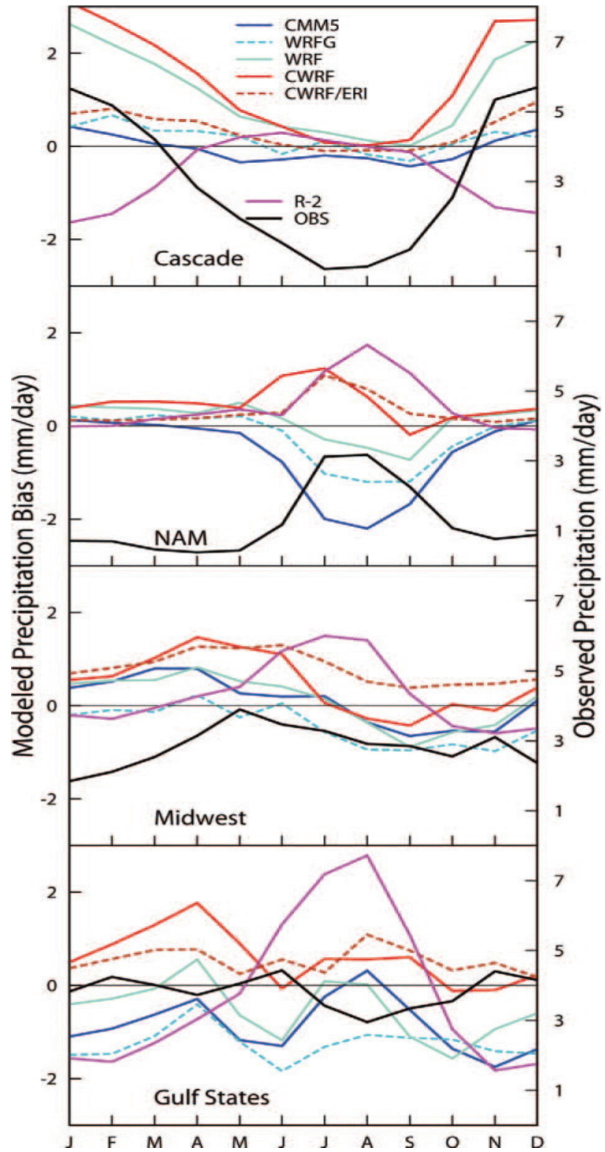

Figure 1.1.7.1. The 1982–2004 mean annual cycle of precipitation biases (mm day^{-1}, left hand scale) simulated by the models, and the observed precipitation (mm day^{-1}, right hand scale) averaged over the four key regions. Also shown are the CWRF/ERI biases averaged during 1990–2008. The zero line only pertains to the left axis. Reprinted with permission from Liang, X.Z., Xu, M., Yuan, X., Ling, T., Choi, H.I., Zhang, F., Chen, L., Liu, S., Su, S., Qiao, F., He, Y., Wang, J.X.L., Kunkel, K.E., Gao, W., Joseph, E.E., Morris, V., Yu, T.-W., Dudhia, J., and Michalakes, J. 2012. Regional climate-weather research and forecasting model. *Bulletin of the American Meteorological Society* **93**: 1363–1380, Figure 4.

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1.1.8 Seasonal Projection

Climate models are tested and reworked with the goal of developing ever-more-accurate representations of how the real world operates, so as to be able to make confident projections of Earth's future climate.

Kim *et al.* (2012) write, "the seasonal prediction skill for the Northern Hemisphere winter [was] assessed using retrospective predictions (1982–2010) from the ECMWF System 4 (Sys4) and [the] National Center for Environmental Prediction (NCEP) CFS version 2 (CFSv2) coupled atmosphere-ocean seasonal climate prediction systems." The analysis revealed "for the Sys4, a cold bias is found across the equatorial Pacific"; "the CFSv2 has [a] strong warm bias from the cold tongue region of the Pacific to the equatorial central Pacific and [a] bias in broad areas of the North Pacific and the North Atlantic."

The researchers also found, "a cold bias over large regions of the Southern Hemisphere is a common property of both reforecasts"; "with respect to precipitation, the Sys4 produced excesses along the Intertropical Convergence Zone, the equatorial Indian Ocean and the western Pacific"; "in the CFSv2, a strong wet bias is found along the South Pacific Convergence Zone and the southern Indian Ocean, as well as in the western Pacific"; "a dry bias is found for both modeling systems over South America and northern Australia and wet bias[es] in East Asia and the equatorial Atlantic"; and "both models have difficulty in forecasting the North Atlantic Oscillation and the year-to-year winter temperature variability over North America and northern Europe."

Reference

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1.2 Modeling Techniques

Researchers are improving the ability of GCMs to simulate the large-scale climate and its interannual variability. However, the models still cannot adequately simulate phenomena that arise from smaller-scale processes such as precipitation, even in areas where precipitation is quite frequent, such as the East Asian Monsoon region. Efforts are continually being made to improve the portrayal of regional climates, model physics and parameterizations, and even the representations of the equations themselves. This section describes some of the studies exploring the subject of model improvement.

1.2.1 Downscaling

One technique developed to improve model performance is called downscaling, a process by which a regional climate model is used over a limited area but with a higher resolution, allowing smaller-scale atmospheric processes to be represented more faithfully, giving the regional climate scenario a finer structure. Downscaling allows an examination of model performance (validation) and a look at the finer-scale details of the projections (e.g. Christensen *et al.* 2007).

One limitation of this technique, however, is that each of the lower-resolution errors and scale-matching at the grid boundary travel to the interior of the finer-resolution portion of the grid and, to some degree, confound the outcome. Given the short time for these errors to propagate inwards and the long duration of climate simulations, this is an unresolved problem that must be addressed.

Zou *et al.* (2010) sought to determine whether downscaling can improve a GCM's ability to replicate the climatology of East Asian Monsoon precipitation. The authors used the LMDz4 model from the Laboratoire de Meteorologie Dynamique in France. This GCM can be run with a coarse grid (1.125 degrees latitude and longitude, or roughly 125 km) or it can be run in "zoom" mode such that the regional area has a grid resolution of about 50 km. The regional simulation has a grid resolution similar to that of a weather forecast model.

Zou *et al.* ran the model for the East Asia Region for the years 1958–2000 in order to compare the modeled climate to monthly observations from this region over the same time period. The raw output revealed the model produced more (less) precipitation when downscaling was (not) used. When the authors extracted the larger-scale component of the precipitation signal from the precipitation data (Figure 1.2.1.1), they found the model results without downscaling were unable to adequately represent the monsoon pattern or its variability (compare Figure 1.2.1.1 frames a, b to frames e, f). The downscaling results (Figure 1.2.1.1 frames c, d) compared more favorably.

Even though the results were an improvement, flaws remained. As Zou *et al.* point out, "it should be acknowledged that our results of dynamic downscaling are not perfect," while adding "the main weakness of the downscaling is the northward shift of the monsoon rainbelt." Although downscaling improves some aspects of the performance of models and their ability to represent observations, this technique is still subject to the general limitations suffered by all numerical models.

Indeed, numerous errors permeate numerical models for both weather forecasts and climate projections. These fall under three headings, (1) observational error, (2) numerical error, and (3) physical error.

Observational error refers to the fact that instrumentation cannot measure the state of the atmosphere with infinite precision; it is important both for establishing the initial conditions and validation. *Numerical error* covers many shortcomings including "aliasing," the tendency to

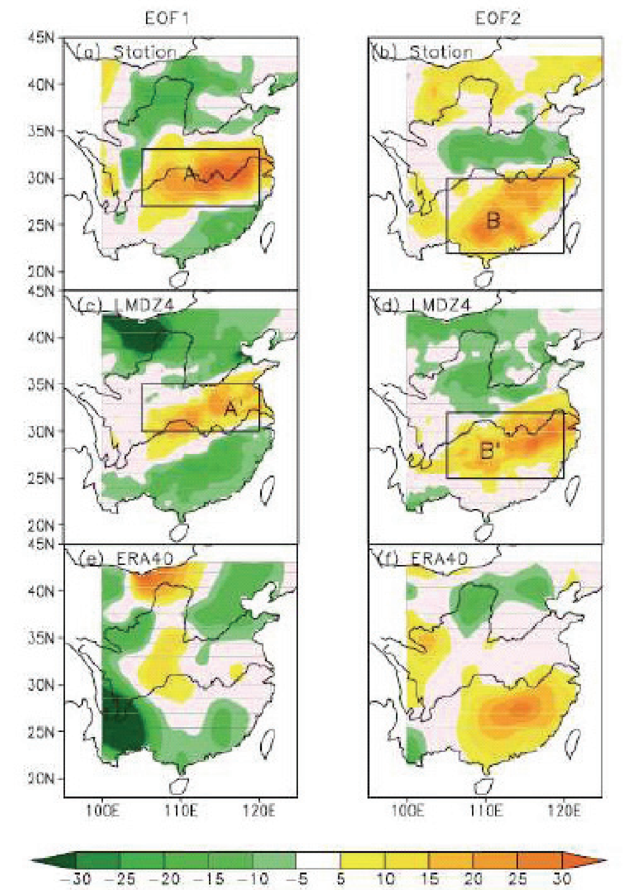

Figure 1.2.1.1. The strongest (left) and second strongest (right) component of summer season precipitation shown as a percentage from the rain gauge observations (top), the GCM with downscaling (middle), and the GCM without downscaling (bottom). Darker (lighter) colors represent more (less) precipitation than the actual measurements. Reprinted with permission from Zou, L., Zhou, T., Li, L., and Zhang, J. 2010. East China summer rainfall variability of 1958–2000: Dynamical downscaling with a variable resolution AGCM. *Journal of Climate* **23**: 6394–6408, Figure 4.

misrepresent the sub-grid scale processes as larger-scale features. In the downscaling approach, presumably errors in the large-scale boundary conditions also will propagate into the nested grid. Also, the numerical methods themselves are only approximations to the solution of the mathematical equations, and this results in truncation error. *Physical errors* are manifest in parameterizations, which may be approximations, simplifications, or educated guesses about how real processes work. An example of this type of error would be the representation of cloud formation and dissipation in a model, which is generally a crude approximation.

Each of these error sources generates and propagates errors in model simulations. Without some "interference" from model designers, model solutions accumulate energy at the smallest scales of resolution or blow up rapidly due to computational error. In weather prediction, techniques have been developed to "smooth" and massage the data during a simulation by removing as much grid-scale energy as possible while retaining the character of the larger scale. Nonetheless, computational error does prevent models from forecasting perfectly, and this explains why two different models (or even two different runs with the same model) can give two different answers given the same or similar set of initial conditions.

Otte *et al.* (2012) use a technique called "nudging" to improve the performance of a weather forecasting model (Weather Research and Forecasting model—WRF) for use in downscaling. Nudging is used to keep the regional model results within the bounds of the larger-scale model results.

Generally applied to the boundaries of a model, Otte *et al.* applied the nudging technique to the interior of the grids. To test the procedure, they used a coarse analysis data set from the National Centers for Environmental Prediction to initialize the regional model. These analyses stood as a proxy for GCM output. They then compared their results to two fine-scale regional re-analyses for North America.

This modeling technique generated a better representation of monthly means and improved interannual variability. The simulations of hot and cold extremes, as well as wet and dry extremes, were captured better in the nudged WRF. However, Otte *et al.* note, "all WRF runs overpredicted precipitation totals through the multidecadal period … regardless of whether nudging was used" (see Figure 1.2.1.2). Fewer false alarms of severe precipitation events were produced with the nudging technique than when it was not used, an important result given that most impacts on society result from the occurrence of extreme events. Reliable simulations that include the realistic occurrence of extremes are valuable for economic planners.

In spite of the success of the nudging employed by Otte *et al.* (2012), their results demonstrate modeling today's climate cannot be done either on the largest scales or regionally without some way of "tuning" the model. This entails using parametric means to force the model to adequately represent reality. Although downscaling can be a valuable tool for regional climate simulations, this newfound ability

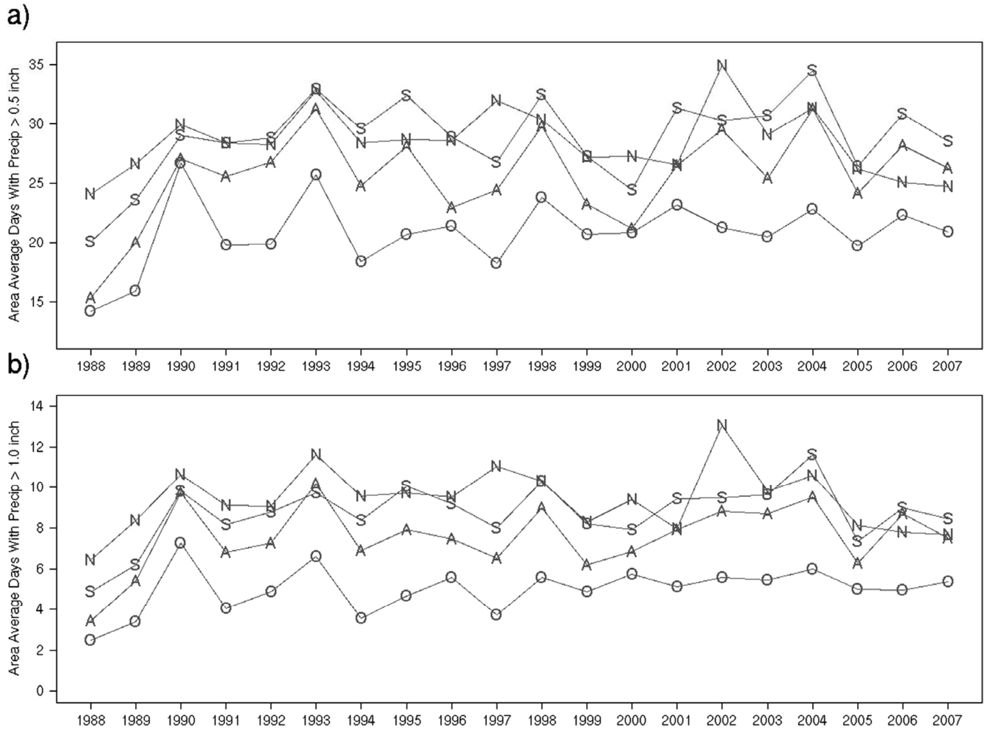

Figure 1.2.1.2. The annual area-averaged number of days with (a) precipitation greater than (a) 0.5 in, and (b) 1.0 in for the Midwest region. Data are shown from North American Regional Reanalyses (O) and WRF runs for no nudging (N), nudging toward analyses (A), and spectral nudging (S). Adapted from Otte, T.L., Nolte, C.G., Otte, M.J., and Bowden, J.H. 2012. Does nudging squelch the extremes in regional climate modeling? *Journal of Climate* **25**: 7046–7066, Figure 13.

is meaningless if the GCM results that are being downscaled are themselves unrealistic.

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Otte, T.L., Nolte, C.G., Otte, M.J., and Bowden, J.H. 2012. Does nudging squelch the extremes in regional climate modeling? *Journal of Climate* **25**: 7046–7066.

Zou, L., Zhou, T., Li, L., and Zhang, J. 2010. East China summer rainfall variability of 1958–2000: Dynamical downscaling with a variable resolution AGCM. *Journal of Climate* **23**: 63946408.

1.2.2 The Dynamic Core

An atmospheric model, whether a forecast model or one used to diagnose which processes drive the climate, is built on a foundation of three main conservation principles: Within the Earth-atmosphere system, mass, energy, and momentum must be conserved. These basic physical principles are represented by a closed set of equations termed the primitive equations. The equations form the "dynamic core" of climate models and represent the motions of air within the model. The model output is generally some variable representing mass (pressure), temperature, or both.

The primitive equations are too complex in their raw form to be represented adequately in models and are often simplified following the concept of Occam's Razor: They are simplified as much as possible, and no more. One way these equations have been simplified is to "linearize" them, thereby eliminating nonlinearity that can make a computer model unstable. This nonlinearity is a process by which the atmosphere behaves in a chaotic fashion. It is also the reason computational errors propagate and amplify. The falsely generated energy interacts across all scales of motion to distort the path of the model evolution such that eventually the scales of motion of interest (weather systems) have only limited forecast relationship to that of the atmosphere they are attempting to reproduce. This is the predictability barrier.

Kondrashov *et al.* (2011) used a simplified three-level atmospheric circulation model designed by Marshall and Molteni (1993) to show the evolution of the wind fields. The model has a fairly coarse horizontal and vertical resolution by today's standards, but it has been shown to represent the largest scales of the atmosphere's climate in a fairly realistic way. The experiment here examined the tendencies of the 500 hPa mass field (streamfunction) due to linear and nonlinear processes. The nonlinear processes were divided into those that are resolvable by the model and those that are of smaller scale than can be represented by the model.

The model output was slightly different depending on which processes were included in the model run. A comparison of the full nonlinear processes or interactions (Figure 1.2.2.1a) gave slightly different results than when comparing only nonlinear resolvable processes (Figure 1.2.2.1b). The model output also differed from that of two similar studies because of the strategies used to calculate these model "climates." The authors conclude the article by stating "the manner of defining interactions between the resolved and unresolved modes plays a crucial role in the dynamical interpretation of the tendency-based statistical diagnostics."

The basic lesson to be learned from the authors' closing statement is that there can be output differences produced within the same model core even when using the same input data, depending on how the nonlinear processes are represented. If the representation of climate can be different depending on how these core processes are represented, then producing model scenarios on the time scale of a century must be done very cautiously and interpretation of the results done carefully.

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Kondrashov, D., Kravtsov, S., and Ghil, M. 2011. Signatures of nonlinear dynamics in an idealized atmospheric model. *Journal of the Atmospheric Sciences* **68**: 3–12.

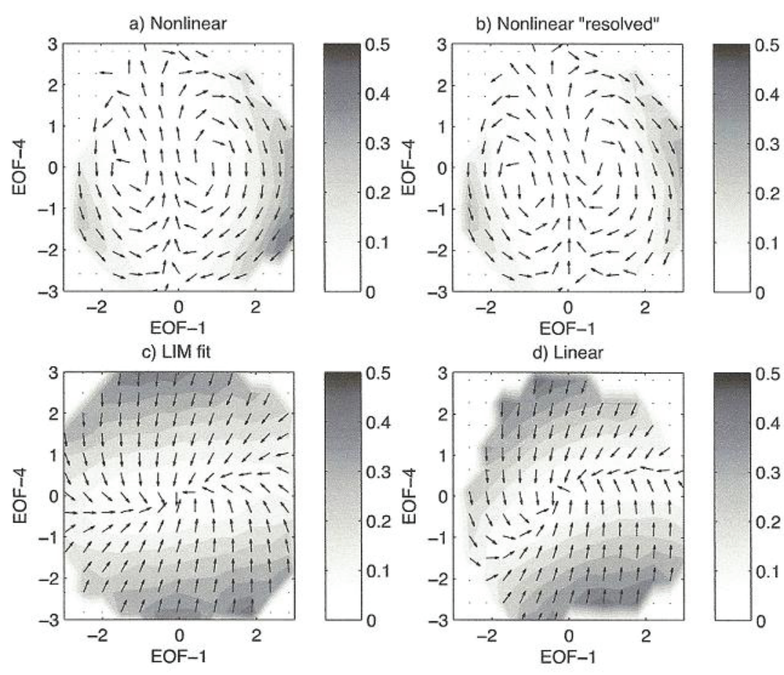

Figure 1.2.2.1. The mean tendencies (model output) in the phase space (mathematical space, not physical), for (a) tendencies due to the full nonlinear processes,(b) nonlinear processes that are resolvable, (c) the linear inverse model output, and (d) the linear part of the nonlinear tendencies. Adapted from Kondrashov, D., Kravtsov, S., and Ghil, M. 2011. Signatures of nonlinear dynamics in an idealized atmospheric model. *Journal of the Atmospheric Sciences* **68**: 3–12.

Marshall, J. and Molteni, F. 1993. Toward a dynamical understanding of atmospheric weather regimes. *Journal of the Atmospheric Sciences* **50**: 1972–1818.

1.2.3 Statistical Models

1.2.3.1 Statistical Validation

The Intertropical Convergence Zone (ITCZ) is an important feature in the atmosphere's general circulation. The ITCZ is a belt of low pressure near the equator where the northeast and southeast trade winds from the Northern and Southern Hemispheres converge. The ITCZ is also characterized by light winds and intermittent regions of convective activity. In some parts of the globe it is easy to identify and in other parts it is more difficult, as it is ill-defined.

This feature is important to the climate system because convection in the ITCZ is the vehicle by which the excess heat and momentum of the tropics begins the journey poleward so as to keep the energetics of the climate system in balance. The ITCZ, which migrates northward in the tropics from January to July (and back southward in July to January), is also an important contributor to the occurrence of the monsoons and often serves as the producer of seed disturbances that become tropical cyclones. Thus it would be important for any study of climate to be able to identify and understand the dynamics of this feature.

Bain *et al.* (2011) used satellite data to develop a modeling tool that can be used to objectively and reliably locate the ITCZ. They used images derived from reflected light (visible—VIS) and radiated energy (infrared images—IR) from Earth. They also used images generated by the intensity of microwave emission and measuring the return (water vapor depth –WV). They limited their domain to the Eastern Pacific from the International Dateline to South America, over the period 1995–2008.

In the model, the presence of the ITCZ was inferred based on the most likely location prior to analysis. Then a point was labeled as ITCZ or non-ITCZ by testing the value of the satellite data typical for the ITCZ, as well as the status of the surrounding grid points in both time and space. A second pass of the dataset blended the *a priori* information with the satellite data and the likelihood that a particular point was ITCZ or non-ITCZ. The method was then evaluated against manual observation and identification of the ITCZ (see Figure 1.2.3.1.1).

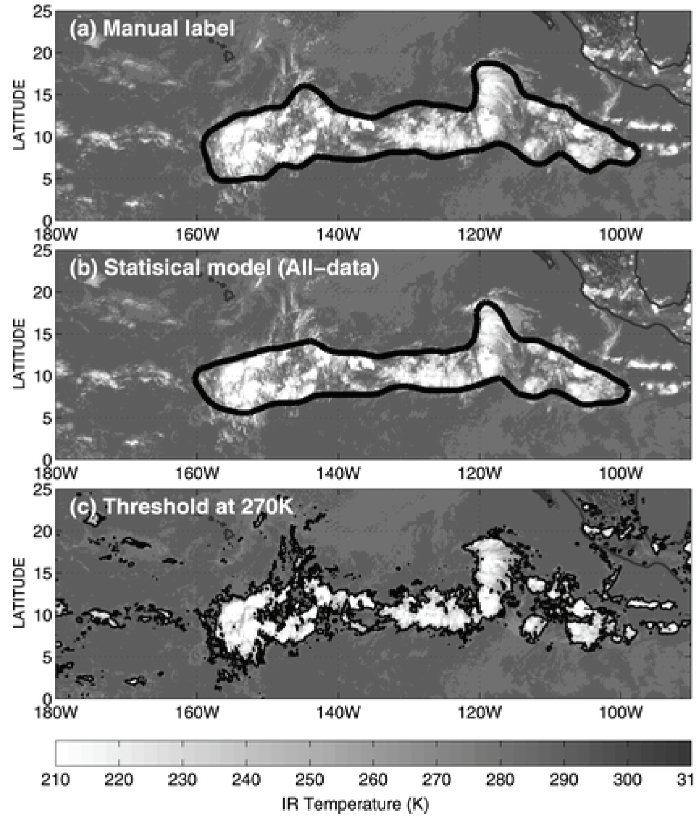

Figure 1.2.3.1.1. The ITCZ cloudiness for 2100 UTC 19 August 2000 overlaid on the IR data for (a) the manual detection, (b) the statistical model from the IR, VIS, and WV satellite data, and (c) the threshold at 270 Kelvin without post-processing. The gray-scale bar below represents the temperatures in the image, and the bold contour in (a) and (b) the position of the ITCZ. Adapted from Bain, C.L., J. DePaz, J. Kramer, G. Magnusdottir, P. Smyth, H. Stern, and C.-C. Wang, 2011. Detecting the ITCZ in instantaneous satellite data using spatiotemporal statistical modeling: ITCZ climatology in the East Pacific. *Journal of Climate* **24**: 216–230, Figure 3.

The statistical methodology of Bain *et al.* tested very well in objectively identifying the ITCZ and was subsequently used to examine the climatological characteristics of the ITCZ. The seasonal evolution of the ITCZ as determined by the methodology showed it migrated with the seasons and its passage followed the seasonal location for the regions of warm sea surface temperatures (SSTs). In order to look at the climatological trends and interannual variations, Bain *et al.* extended the satellite data set back to 1980 for the IR data only. In doing so they found there was enhanced (less) ITCZ convection in El Niño (La Niña) years, a finding reached in previous studies. However, they found "no climatic shifts in the position of the ITCZ could be detected," which suggests, they write, "any trends in the ITCZ location over the 30 years (that are not due to ENSO) are quite small or non-existent."

Thus, statistical modeling can be used to objectively identify, in more detail, important features of the general circulation that we previously thought were well-known. The successful design of a model to objectively locate the ITCZ will be useful in the future study of its dynamics as well as its interaction with other tropical features such as the monsoons or the Madden Julian Oscillation (MJO), which manifests as a 30- to 60-day oscillation in tropical convection. Not all models are dynamic, and not all models are used to project the future climate. But using this particular model, Bain *et al.* showed no significant change in the character of the ITCZ in the past 30 years over the tropical Eastern Pacific.

Reference

Bain, C.L., J. DePaz, J. Kramer, G. Magnusdottir, P. Smyth, H. Stern, and C.-C. Wang, 2011. Detecting the ITCZ in instantaneous satellite data using spatiotemporal statistical modeling: ITCZ climatology in the East Pacific. *Journal of Climate* **24**: 216–230.

1.2.3.2 Empirical Models

Models can be analytical, statistical, or empirically derived and are then used to examine trends or cycles in a time series in an effort to determine the causes of change or variability.

Loehle and Scafetta (2011) built a one-dimensional model of global temperatures from 1850 to 2010 using the inductive approach and used this model to project the change in climate from the current time to the year 2100. The authors constructed their model using what they called "decomposition analysis," based on a method of cycles and used in identifying cyclic behavior in a time series.

Previous research from each author and their colleagues had found there are cyclic and quasi-cyclic forcing processes that can be extracted from local and global time series of temperature. Such cycles can be related to solar and astronomical activity (for example 11, 22, 50–80 years; see Chapter 3 of this volume), or terrestrial oscillations such as the Pacific Decadal Oscillation (about 60 years). Their earlier research pointed to the presence and dominance of 20- and 60- year cycles in temperature time series. Their model also identified a linear trend that may be related to solar and volcanic activity since the middle of the Little Ice Age. Additionally, they included an anthropogenic trend emerging in the early 1940s (Figure 1.2.3.2.1). These four processes combined to produce a model that fit the global temperature series from 1850 to 2010 very well.

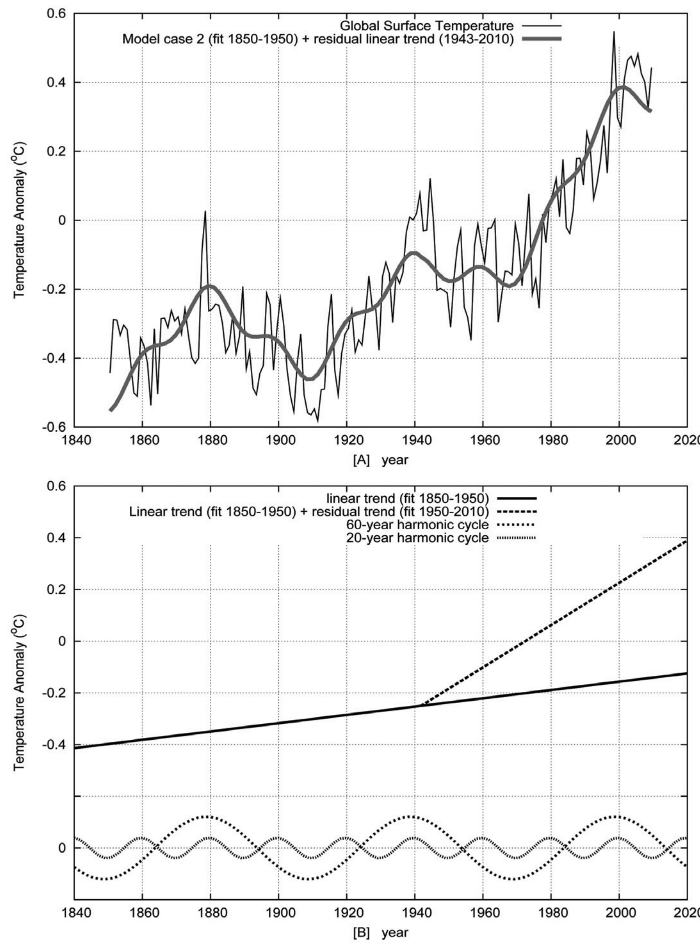

Figure 1.2.3.2.1. (Top) A full reconstruction of the global temperature anomaly (°C) record of 1850 -2010 using the model described by Loehle and Scafetta (2011). (Bottom) The individual components of the model, where the solid line is the long term trend and the dashed line is the anthropogenic component. Adapted from Loehle, C. and Scafetta, N. 2011. Climate change attribution using empirical decomposition of climatic data. *The Open Atmospheric Science Journal* **5**: 74–86, Figure 3.

Loehle and Scafetta determined that more than 50 percent and as much as 60 percent of the climate signal from 1850 to 2010 was the product of natural forcing. They projected future climate to the year 2100 using the model, stating, "the result is a continued warming with oscillations to a high in 2100 of about 0.6°C above 2000 values." This resulted from the combined effect of natural and anthropogenic forcing.

The 0.6°C temperature rise projected by the Loehle and Scafetta model is much less than the low-end estimates of 2.3°C projected by the GCMs relied upon by the IPCC and is consistent with recent estimates of low climate sensitivity. Also, the Loehle and Scafetta model shows the latest downturn in temperatures since 2000. The IPCC (2007) models do not show this downturn and assume 90 percent or more of the climate change since 1970 is anthropogenic. As Loehle and Scafetta point out, "we have shown that the effect of natural oscillations is critical for proper assessment of anthropogenic impacts on the climate system." Perhaps this is why Loehle and Scafetta's model fits the historic temperature data much better than do most of the IPCC models, and with far fewer parameters.

Several studies have shown GCMs are improving in their ability to reproduce the current climate, including intraseasonal and interannual variations. The ability of the GCMs to capture internal nonlinear processes, however, will always be suspect.

But when examining climate, important external forcing processes need to be accounted for, including such natural processes as volcanic activity and solar variations. There is increasing evidence that extraterrestrial forcing processes can have an impact on solar variations and, thus, terrestrial climate.

Recent work by Scafetta (2011) explores several such issues. First, the author expanded on his own work demonstrating a link between well-known climate cycles of roughly 10, 20, and 60 years to celestial cycles. The celestial cycles result from the solar-lunar tidal oscillation (9.1 years) and gravitational cycles related to the interaction between the sun and the largest planets (Jupiter and Saturn). These celestial cycles have periods of about 10, 20, and 60 years. Loehle and Scafetta (2011) demonstrated these cycles can be added together and, with a realistic anthropogenic effect, reconstruct the global climate record since 1950. They also show this empirical model can be used to project climate into the twenty-first century.

Scafetta also demonstrated the IPCC GCMs cannot capture decadal and interdecadal variability. As shown by the author (see Figure 1.2.3.2.2), "although these GCM simulations present some kind of red-noise variability supposed to simulate the multi-annual, decadal, and multidecadal natural variability, a simple visual comparison among the simulations and the temperature record gives a clear impression that the simulated variability has nothing to do with the observed temperature dynamics."

Scafetta then demonstrates natural variability is not solely the result of internal variations; the external forcing described above also plays a role. These external forcings modulate solar output, which in turn impacts electrical activity in the upper atmosphere. This influences incoming cosmic ray fluxes, which have been linked to variability in cloudiness. The external cycles have periods similar to internal climate variations. Natural variations then, likely account for more than half the climate variability since 1850.

Finally, Scafetta also demonstrated the IPCC is erroneous in ascribing nearly all of the twentieth and twenty-first century climate change to anthropogenic forcing. When the anthropogenic effect is corrected, it accounts for less than half the recent climate change. Scafetta also showed his empirical model projected the cooling of the most recent decade, whereas the IPCC GCMs produced a quasi-monotonic warming of the climate from about the year 2000 on. Scafetta's model produces a warming of only 0.8–1.5° C by the end of the twenty-first century.

Scientists skeptical of the IPCC's projections of anthropogenic climate change have cautioned the public about the shortcomings of the IPCCs reliance on GCMs in producing climate change scenarios for the next century. In addition to well-documented problems with model numerics, the lack of data, and chaos, the physics of the models fall short. This is true not only for such internal processes as cloud physics, but also for such external forcing as Sun-moon tidal forcing and other solar system gravitational cycles that influence solar output.

Scafetta's work demonstrates there is increasing evidence our solar system plays a significant role in decadal and multidecadal climate variations. The climate projections produced by Scafetta's empirical harmonic model may be far more realistic and are certainly more optimistic.

References

IPCC. 2007. *Climate Change 2007 -I: The Science of Basis, Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K, Tignor, M.M.B., Miller, H.L. Jr., and Chen, Z.. Cambridge University Press, Cambridge, UK.

Loehle, C. and Scafetta, N. 2011. Climate change attribution using empirical decomposition of climatic data. *The Open Atmospheric Science Journal* **5**: 74–86.

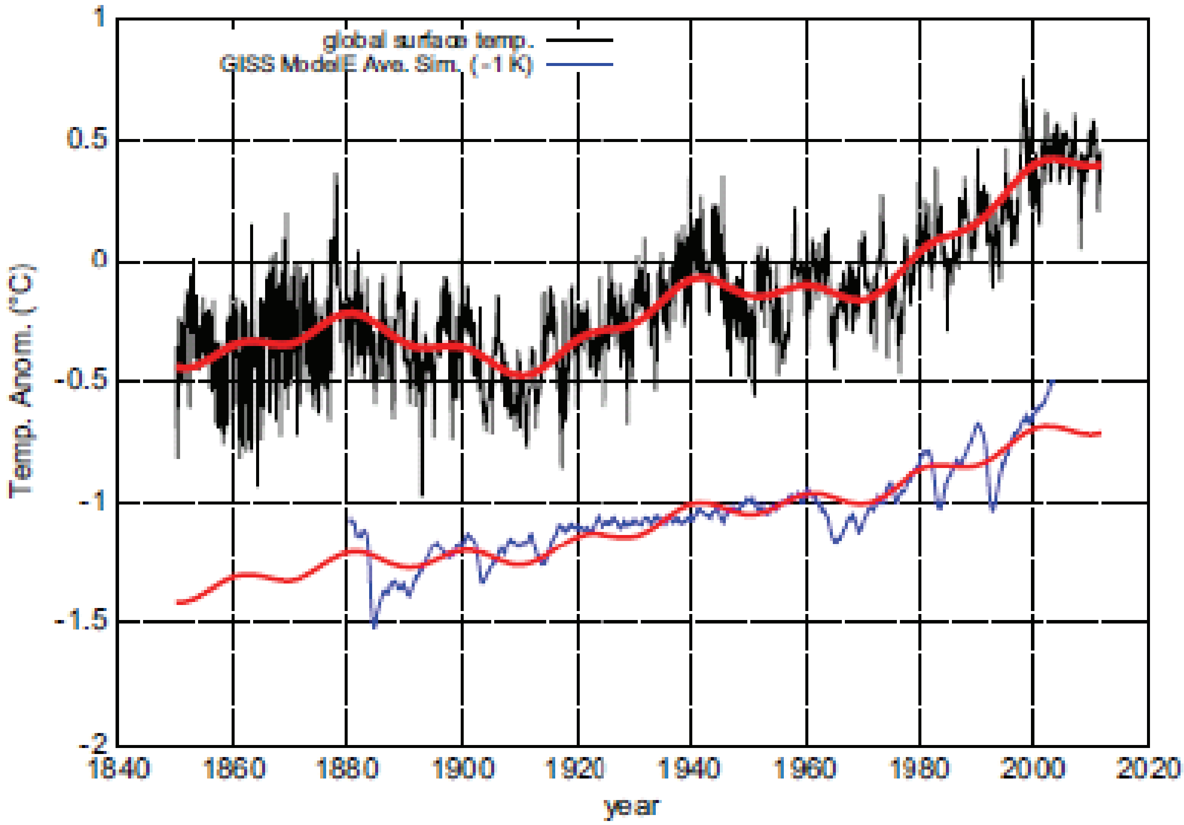

Figure 1.2.3.2.2. The global surface temperature taken from *http://www.cru.uea.ac.uk/cru/data/temperature/* (black) and the GISS ModelE average simulation (blue), and a fit using an empirical harmonic model (red). Reprinted with permission from Scafetta, N. 2011. Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation models. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 124–137, Figure 1.

Scafetta, N. 2011. Testing an astronomically based decadal-scale empirical harmonic climate model versus the IPCC (2007) general circulation models. *Journal of Atmospheric and Solar-Terrestrial Physics* **80**: 124–137.

1.2.4 Low Order Models

In meteorology it is well-known that the limit of dynamic predictability is approximately 10 to 14 days. This constraint is imposed by the composition of our atmosphere and the size of the planet. However, there has been some disagreement in the climate community over whether there is a fair amount of predictability in climate or whether it is too chaotic for meaningful prediction. It is appropriate here to revisit a classic work written by E.N. Lorenz nearly 50 years ago on the subject of predictability in atmospheric flows.

At the time, meteorology was interested in explaining why the mid-latitude flow (jet stream) would transition from a higher amplitude state to a more zonal state in an irregular fashion at a time scale of roughly 10 to 14 days. There was also some interest in being able to make monthly and seasonal forecasts, which during the late 1950s to 1960s were considered very long range. During this time, numerical weather prediction was also in its infancy.

Lorenz (1963) was expressly interested in examining the behavior of periodic and non-periodic flows. Later Lorenz would describe the non-periodic behavior as “chaos,” which he then termed “*order without periodicity*.”

He used a technique called low order modeling to study the behavior of convection in a geophysical fluid. To do so he coupled the Equation of Motion and the First Law of Thermodynamics and then represented the motion and temperature variables in terms of waves, which were then characterized by the lowest wave numbers that reasonably represented these fields. He was able to demonstrate the solutions for the system in mathematical space and thus follow the evolution of the system in time. The resultant graph is commonly known today as Lorenz's butterfly (Figure 1.2.4.1). He realized this model provided a good analogue for the behavior of mid-latitude flow.

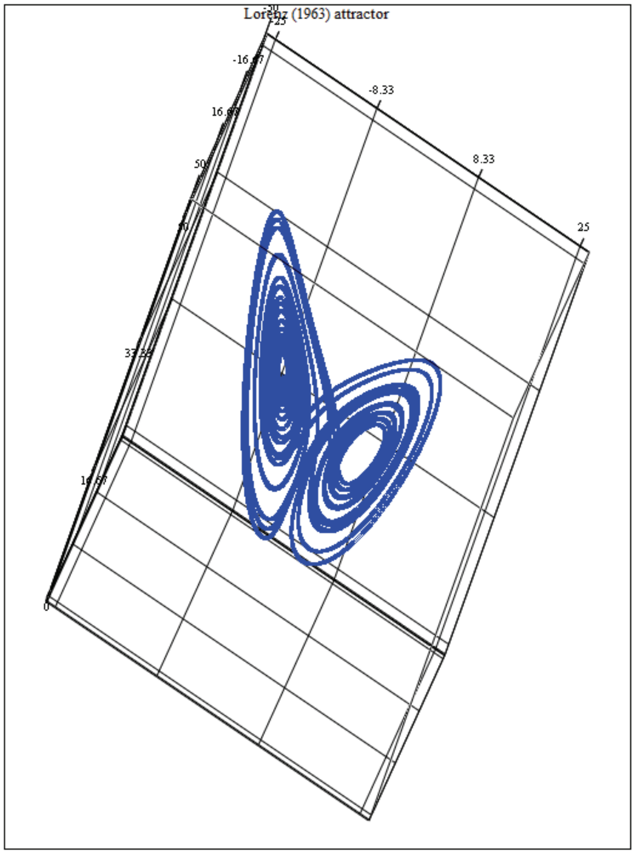

Figure 1.2.4.1. A representation of Lorenz's butterfly developed using the model published in Lorenz (1963). This figure was created in the Weather Analysis and Visualization (WAV) Lab at the University of Missouri.

In theory, then, if we know the precise initial conditions of the system such that we lay on one of the trajectories in the "butterfly," we could follow that trajectory forever and know what the state of the weather would be into the future infinitely. Computers could then make weather or climate forecasts, and meteorologists would be out of jobs.

However, even today's best models are comprised only of hypotheses about how scientists believe the atmosphere really works. As the past has made abundantly clear, state-of-the-art models of "today" quickly outlive their usefulness and are eventually replaced by the newer and improved models of "tomorrow." Today's best representation of the physics is inadequate and there are also numerical model errors, in that differential quantities can only be estimated.

But the crux of predictability rests in the fact that the initial conditions are not precisely known. There is always a degree of uncertainty within them, and thus it is not known on which trajectory the model rests. According to Lorenz, "when our results concerning the instability of non-periodic flow are applied to the atmosphere, which is ostensibly nonperiodic, they indicate that prediction of the sufficiently distant future is impossible by any method, unless the present conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long-range forecasting would seem to be non-existent." The problem of not being able to specify the precise initial state—sensitive dependence on initial conditions (SDIC)—is an integral characteristic of chaotic systems.

Lorenz's statement makes it plain that beyond 10 to 14 days, the typical timescale for the evolution of the mid-latitude flow, dynamic predictability is impossible. This is true in spite of the fact we can specify the equations representing motions in the flow. Such limits on predictability are thus scale-dependent. For example, because of their small spatial scales, we cannot dynamically predict the occurrence of individual thunderstorms beyond the 30- to 120-minute time-scale it takes for them to evolve. Beyond the time limits, corresponding to the appropriate space-scale, only statistical prediction is useful.

One way modelers attempt to mitigate SDIC is via the use of ensemble modeling. The technique is to take the initial conditions and several plausible alternative initial conditions (but very close by to the original) and run the model several times using each set. If the trajectories all evolve toward a common trajectory, the modelers claim there is high confidence that the predicted solution is highly probable. But when these trajectories diverge (another characteristic of chaotic systems), the probability that any one of them will be the actual prediction is small. Model runs of climate change scenarios exhibit this latter behavior. In these projections, the spread in the forecasts gets larger and larger as the projection time horizon lengthens. This is exactly the behavior expected from models attempting to simulate nonlinear flow—the energy of eddies below the grid scale appears chaotically as eddies on scales of the motion resolved by the grid.

Thus there is ample evidence the climate behaves in a chaotic way and climate prediction is simply not possible; only the development of *scenarios* is possible. Although these scenarios might be statistically similar to the real climate (as opposed to accurate in detail), this observation remains to be demonstrated and cannot be assumed.

Reference

Lorenz, E.N. 1963. Deterministic nonperiodic flow. *Journal of Climate* **20**: 130–139.

1.2.5 Bias Correction

In a *Hydrology and Earth System Sciences* opinion article, Ehret *et al*. (2012) write, "despite considerable progress in recent years, output of both global and regional circulation models is still afflicted with biases to a degree that precludes its direct use, especially in climate change impact studies," noting "this is well known, and to overcome this problem, bias correction (BC, i.e., the correction of model output towards observations in a post-processing step) has now become a standard procedure in climate change impact studies." For example, GCMs often produce a global climate that is too cool or too warm by several degrees compared to the real world.

Ehret *et al.* present "a brief overview of state-of-the-art bias correction methods, discuss the related assumptions and implications, draw conclusions on the validity of bias correction and propose ways to cope with biased output of circulation models."

In discussing the findings of their review, the authors state: (1) "BC methods often impair the advantages of circulation models by altering spatiotemporal field consistency, relations among variables and by violating conservation principles," (2) "currently used BC methods largely neglect feedback mechanisms, (3) "it is unclear whether they are time-invariant under climate change conditions," (4) "applying BC increases agreement of climate model output with observations in hindcasts and hence narrows the uncertainty range of simulations and predictions," but (5) this is often done "without providing a satisfactory physical justification," and this sleight of hand "is in most cases not transparent to the end user." For example, the temperatures produced by GCMs are presented as anomalies in the IPCC reports so their disagreement with each other and with the real world are hidden.

Ehret *et al*. argue this set of negative consequences of bias correction "hides rather than reduces uncertainty," which they suggest may lead to avoidable forejudging of end users and decision makers. They conclude BC is often "not a valid procedure."

Reference

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J. 2012. Should we apply bias correction to global and regional climate model data? *Hydrology and Earth System Sciences* **16**: 3391–3404.

1.3 Elements of Climate

GCMs must incorporate all the many physical, chemical, and biological processes that influence climate over different spatial and temporal scales. Although the models have evolved much in recent years, limitations and deficiencies remain.

Many important processes are either missing or inadequately represented in today's state-of-the-art climate models. Here we highlight many of the insufficiencies researchers have found when comparing model projections against real-world observations, frequently using the researchers' own words to report them. The list is long and varied, and it demonstrates much work remains to be done before the model simulations can be treated with the level of confidence ascribed to them by the IPCC.

1.3.1 Radiation

One of the most challenging and important problems facing today's general circulation models of the atmosphere is how to accurately simulate the physics of Earth's radiative energy balance. In commenting on this task, Harries (2000) stated more than a decade ago, "progress is excellent, on-going research is fascinating, but we have still a great deal to understand about the physics of climate." He added, "we must exercise great caution over the true depth of our understanding, and our ability to forecast future climate trends." As an example, he points out our knowledge of high cirrus clouds is very poor (it remains so today), noting "we could easily have uncertainties of many tens of W m^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing."

Potential errors of this magnitude are extremely disconcerting in light of the fact that the radiative effect of a doubling of the air's CO_2 content is in the lower single-digit range of Wm^{-2}, and, to quote Harries, "uncertainties as large as, or larger than, the doubled CO_2 forcing could easily exist in our modeling of future climate trends, due to uncertainties in the feedback processes."

Furthermore, because of the vast complexity of the subject, Harries declares, "even if [our] understanding were perfect, our ability to describe the system sufficiently well in even the largest computer models is a problem."

Illustrative of a related problem is the work of Zender (1999), who characterized the spectral, vertical, regional, and seasonal atmospheric heating caused by the oxygen collision pairs $O_2 \cdot O_2$ and $O_2 \cdot N_2$, which had earlier been discovered to absorb a small but significant fraction of the globally incident solar radiation. This work revealed these molecular collisions lead to the absorption of about 1 Wm^{-2} of solar radiation, globally and annually averaged. This discovery, in Zender's words, "alters the long-standing view that H_2O, O_3, O_2, CO_2 and NO_2 are the only significant gaseous solar absorbers in Earth's atmosphere," and he suggests the phenomenon "should therefore be included in ... large-scale atmospheric models used to simulate climate and climate change." Zender's work also raises the possibility there are still other yet-to-be-discovered processes that should be included in the models used to simulate Earth's climate, and until we are confident there is little likelihood of further such surprises, we ought not rely too heavily on what the models of today are telling us about the climate of tomorrow.

In another revealing study, Wild (1999) compared the observed amount of solar radiation absorbed in the atmosphere over equatorial Africa with what was predicted by three general circulation models of the atmosphere. Wild found the model predictions were much too small. Regional and seasonal model underestimation biases were as high as 30 Wm^{-2}, primarily because the models failed to properly account for spatial and temporal variations in atmospheric aerosol concentrations. In addition, Wild found the models likely underestimated the amount of solar radiation absorbed by water vapor and clouds.

Similar large model underestimations were discovered by Wild and Ohmura (1999), who analyzed a comprehensive observational data set consisting of solar radiation fluxes measured at 720 sites across Earth's surface and corresponding top-of-the-atmosphere locations to assess the true amount of solar radiation absorbed within the atmosphere. These results were compared with estimates of solar radiation absorption derived from four atmospheric GCMs. They found "GCM atmospheres are generally too transparent for solar radiation," as they produce a rather substantial mean error close to 20 percent below actual observations.

Another solar-related deficiency of state-of-the-art GCMs is their failure to properly account for solar-driven variations in Earth-atmosphere processes that operate over a range of timescales extending from the 11-year solar cycle to century- and millennial-scale cycles. Although the absolute solar flux variations associated with these phenomena are small, there are a number of "multiplier effects" that may significantly amplify their impacts.

According to Chambers *et al*. (1999), most of the many nonlinear responses to solar activity variability are inadequately represented in the global climate models used by the IPCC to predict future greenhouse gas-induced global warming. Other amplifier effects are used to model past glacial/interglacial cycles and even the hypothesized CO_2-induced warming of the future, where CO_2 is not the major cause of the predicted temperature increase but rather an initial perturber of the climate system that according to the IPCC sets other, more-powerful forces in motion that produce the bulk of the ultimate warming. So there appears to be a double standard within the climate modeling community that may best be described as an inherent reluctance to deal evenhandedly with different aspects of climate change. When multiplier effects suit their purposes, they use them; but when they don't suit their purposes, they don't use them.

In setting the stage for their study of climate model inadequacies related to radiative forcing, Ghan *et al*. (2001) state, "present-day radiative forcing by anthropogenic greenhouse gases is estimated to be 2.1 to 2.8 Wm^{-2}; the direct forcing by anthropogenic aerosols is estimated to be -0.3 to -1.5 Wm^{-2}, while the indirect forcing by anthropogenic aerosols is estimated to be 0 to -1.5 Wm^{-2}," so that "estimates of the total global mean present-day anthropogenic forcing range from 3 Wm^{-2} to -1 Wm^{-2}." This implies a climate change somewhere between a modest warming and a slight cooling. They write, "the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies."

Pursuit of this goal, as Ghan *et al.* describe it, requires achieving "profound reductions in the uncertainties of direct and indirect forcing by anthropogenic aerosols," which is what they set out to do. This consisted of "a combination of process studies designed to improve understanding of the key processes involved in the forcing, closure experiments designed to evaluate that understanding, and integrated models that treat all of the necessary processes together and estimate the forcing." At the conclusion of this laborious set of operations, Ghan *et al*. arrived at numbers that considerably reduced the range of uncertainty in the "total global mean present-day anthropogenic forcing," but still implied a set of climate changes stretching from a small cooling to a modest warming. Thus they provided a long list of other things that must be done in order to obtain a more definitive result, after which they acknowledged even this list "is hardly complete." They conclude their analysis by stating, "one could easily add the usual list of uncertainties in the representation of clouds, etc." Consequently, they write, "much remains to be done before the estimates are reliable enough to base energy policy decisions upon."

Vogelmann *et al*. (2003) also studied the aerosol-induced radiative forcing of climate, reporting, "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux between 7 and 25 Wm^{-2} (Sokolik *et al*., 1998)," but "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al*., 1996; Jacobson, 2001) despite their potentially large forcing." In an attempt to persuade climate modelers to rectify the situation, Vogelmann *et al*. used high-resolution spectra to calculate the surface IR radiative forcing created by aerosols encountered in the outflow of air from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. They determined "daytime surface IR forcings are often a few Wm^{-2} and can reach almost 10 Wm^{-2} for large aerosol loadings," and these values "are comparable to or larger than the 1 to 2 Wm^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times." The researchers conclude their results "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

Two papers published a year earlier (Chen *et al*., 2002; Wielicki *et al*., 2002) revealed what Hartmann (2002) called a pair of "tropical surprises." The first of the seminal discoveries was the common finding of both groups of researchers that the amount of thermal radiation emitted to space at the top of the tropical atmosphere increased by about 4 Wm^{-2} between the 1980s and the 1990s. The second was that the amount of reflected sunlight decreased by 1 to 2 Wm^{-2} over the same period, with the net result that more total radiant energy exited the tropics in the latter decade. In addition, the measured thermal radiative energy loss at the top of the tropical atmosphere was of the same magnitude as the thermal radiative energy gain generally predicted to result from an instantaneous doubling of the air's CO_2 content. Yet as Hartman noted, "only very small changes in average tropical surface temperature were observed during this time."

The change in solar radiation reception was driven by changes in cloud cover, which allowed more solar radiation to reach the surface of Earth's tropical region and warm it. These changes were produced by what Chen *et al*. determined to be "a decadal-time-scale strengthening of the tropical Hadley and Walker circulations." Another factor was likely the past quarter-century's slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean (McPhaden and Zhang, 2002); this circulation slowdown also promotes tropical sea surface warming by reducing the rate of supply of relatively colder water to the region of equatorial upwelling.

What do these observations have to do with evaluating climate models? They provide several new phenomena for the models to replicate as a test of their ability to properly represent the real world. McPhaden and Zhang note the time-varying meridional overturning circulation of the upper Pacific Ocean provides "an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific."

In an eye-opening application of this principle, Wielicki *et al*. tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. No significant decadal variability was exhibited by any of the models and all failed to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test thus conclude "the missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved."

Hartmann is considerably more candid in his scoring of the test, stating the results indicate "the models are deficient." Expanding on that assessment, he further notes, "if the energy budget can vary substantially in the absence of obvious forcing," as it did over the past two decades, "then the climate of Earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models."

Also concentrating on the tropics, Bellon *et al*. (2003) note "observed tropical sea-surface temperatures (SSTs) exhibit a maximum around 30°C" and "this maximum appears to be robust on various timescales, from intraseasonal to millennial." They state, "identifying the stabilizing feedback(s) that help(s) maintain this threshold is essential in order to understand how the tropical climate reacts to an external perturbation," which knowledge is needed for understanding how the global climate reacts to perturbations such as those produced by solar variability and the ongoing rise in atmospheric CO_2 levels. Pierrehumbert's (1995) work confirms the importance of this matter, clearly demonstrating, in the words of Bellon *et al*., "that the tropical climate is not determined locally, but globally." They also note Pierrehumbert's work demonstrates interactions between moist and dry regions are an essential part of tropical climate stability, harking back to the *adaptive infrared iris* concept of Lindzen *et al*. (2001).

Noting previous box models of tropical climate have shown it to be sensitive to the relative areas of moist and dry regions of the tropics, Bellon *et al*. analyzed various feedbacks associated with this sensitivity in a four-box model of the tropical climate "to show how they modulate the response of the tropical temperature to a radiative perturbation." In addition, they investigated the influence of the model's surface-wind parameterization in an attempt to shed further light on the nature of the underlying feedbacks that help define the global climate system responsible for the tropical climate observations of constrained maximum SSTs.

Bellon *et al*.'s work, as they describe it, "suggests the presence of an important and as-yet-unexplored feedback in earth's tropical climate, that could contribute to maintain the 'lid' on tropical SSTs," much like the adaptive infrared iris concept of Lindzen *et al*. They also say the demonstrated "dependence of the surface wind on the large-scale circulation has an important effect on the sensitivity of the tropical system," specifically stating "this dependence reduces significantly the SST sensitivity to radiative perturbations by enhancing the evaporation feedback," which injects more heat into the atmosphere and allows the atmospheric circulation to export more energy to the subtropical free troposphere, where it can be radiated to space.

Clearly, therefore, the case is not closed on either the source or the significance of the maximum "allowable" SSTs of tropical regions; hence, neither is the case closed on the degree to which the planet may warm in response to continued increases in the atmospheric concentrations of carbon dioxide and other greenhouse gases.

Eisenman *et al*. (2007) reported another problem with model treatment of radiation. They used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different GCMs evaluated for the IPCC's *Fourth Assessment Report*. Based on their analysis, they report there was a 40 Wm^{-2} spread among the 16 models in terms of their calculated downward longwave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from one to more than ten meters. They note the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were "forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes?"

Answering their own question, the three researchers state "a frequently used approach" to resolving this problem "is to tune the parameters associated with the ice surface albedo" to get a more realistic answer. "In other words," they continue, "errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components." The three researchers conclude "the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields," and, therefore, "the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice."

Andronova *et al*. (2009) "used satellite-based broadband radiation observations to construct a long-term continuous 1985–2005 record of the radiative budget components at the top of the atmosphere (TOA) for the tropical region (20°S-20°N)." They then "derived the most conservative estimate of their trends" and "compared the interannual variability of the net radiative fluxes at the top of the tropical atmosphere with model simulations from the Intergovernmental Panel on Climate Change *Fourth Assessment Report* (AR4) archive available up to 2000." The three researchers report "the tropical system became both less reflective and more absorbing at the TOA," and "combined with a reduction in total cloudiness (Norris, 2007), this would mean that the tropical atmosphere had recently become more transparent to incoming solar radiation, which would allow more shortwave energy to reach Earth's surface." They also found "none of the models simulates the overall 'net radiative heating' signature of the Earth's radiative budget over the time period from 1985–2000."

With respect to the first of their findings, and the associated finding of Norris (2007), Andronova *et al.* state these observations "are consistent with the observed near-surface temperature increase in recent years," which provides an independent validation of the TOA radiation measurements. With respect to their second finding, the failure of all of the AR4 climate models to adequately simulate the TOA radiation measurements discredits the models. The combination of these two conclusions suggests the historical rise in the air's CO_2 content likely has played a much lesser role in the post-Little Ice Age warming of the world than the IPCC has admitted.

In another paper, Svensson and Karlsson (2012) use several GCMs of various horizontal and vertical resolutions to examine the climate of the Arctic defined as the region north of the Arctic Circle (66.6^o N). They were concerned with modelling the winter months during the period 1980–1999, a time of limited observational data sets. The observations used were the European Centre for Long Range Forecasting (ECMWF) ERA reanalyses. The authors write, "one should be cautious to interpret the data as 'truth' in this remote region. However, the abundance of observations at lower latitudes [in the Arctic] and sea ice extent should at least constrain the properties of the air masses that enter and exit the Arctic." The observational data in this region were augmented with satellite observations.

Svensson and Karlsson found the winter sea ice cover was similar among the models and accorded with observations across much of the Arctic Ocean. However, there were some differences at the margins, and in the North Atlantic the overall result is that most of the models produce too much sea ice. In validating other quantities, it was found the models tend to underestimate the longwave energy being radiated into space, some by as much as 10 percent. In terms of wintertime mean cloudiness, the models generate winter season values between 35 and 95 percent, whereas observations show values ranging from 68 percent to 82 percent, a smaller range. Near the surface, the latent and sensible heat fluxes within the Arctic were consistent with observations.

The vertical profiles (Figure 1.3.1.1) show the models were generally cooler in the lower troposphere and a little more humid. This led to wide differences between models in the characteristics of air masses. Also, all models showed stronger gradients in temperature and humidity than were observed in the lower troposphere, which resulted in lower clear-sky modelled radiation than for observations. One possible explanation was that many of the models were less "active" in terms of synoptic weather patterns in this region. From these findings, the authors infer humidity was the most important contributor to the radiation budgets in the Arctic region. This leads to the conclusion that it is important to know the models are simulating temperature and moisture profiles correctly in this region of the world.

Regional Climate Models (RCMs) are often used to simulate the climate of more limited spatial regions, especially if the focus is on phenomena driven by smaller-scale processes or even microphysical processes. Regional climate models are similar to regional forecast models in much the same way that their general circulation (GCM) counterparts are similar to global forecast models. RCMs suffer from the same deficiencies as all models, including insufficient data and resolution, model physics, and the numerical methods used.

A study by Zubler *et al.* (2011) attempted to demonstrate changes in aerosol emissions over Europe lead to changes in the radiation budgets over the region using the COSMO-CLM model (Doms and Schättler, 2002) RCM. The horizontal and vertical resolution in the RCM was finer than that in a GCM. The RCM was coupled with the aerosol model used by the European Centre for Medium Range Forecasting, Hamburg GCM and included both natural and anthropogenic aerosols. The authors performed two computer runs, one with climatologically averaged aerosols and the other with aerosol emissions that change with time (transient). On the boundaries, the RCM was driven by the European Centre re-analyses (ERA-40).

Zubler *et al.* found under clear sky conditions there was a dimming over Europe due to transient emissions from the late 1950s to the late 1970s, then a

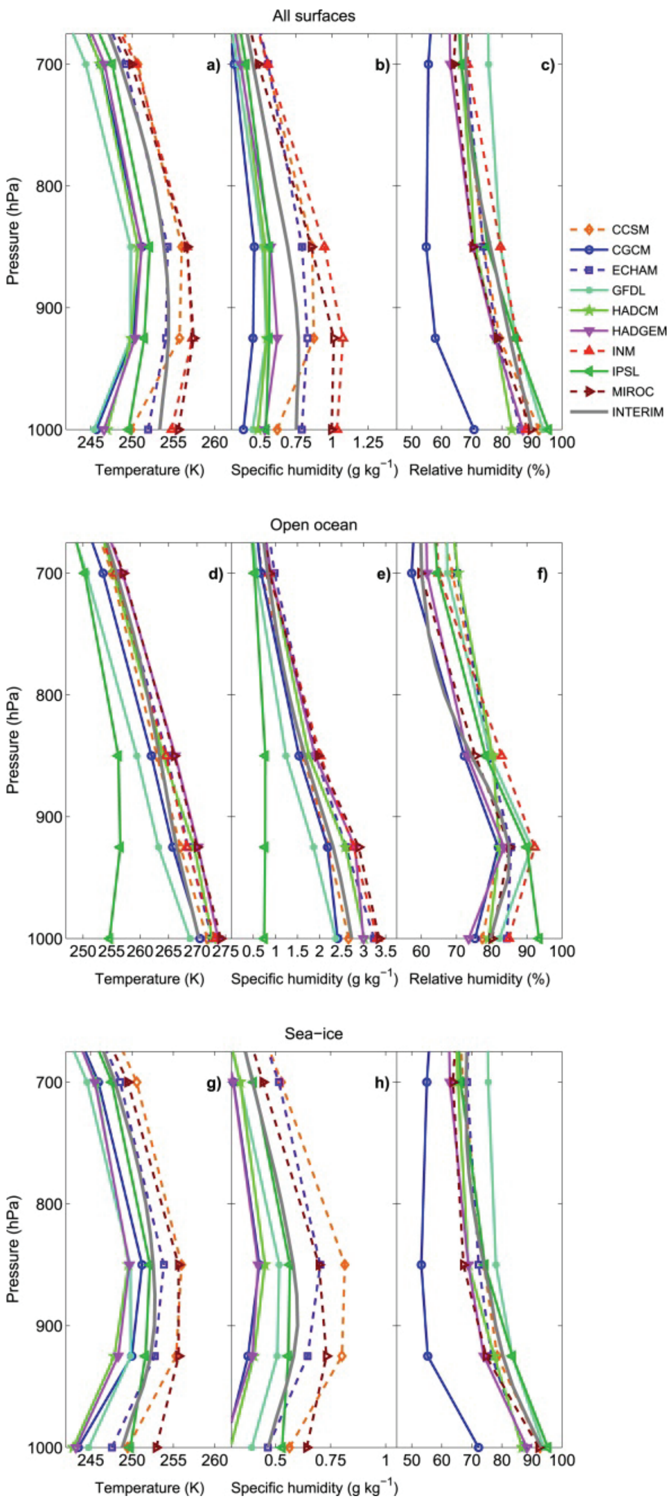

Figure 1.3.1.1. The median vertical profiles for temperature (K), specific humidity (g kg−1), and relative humidity over (a)–(c) entire Arctic, (d)–(f) open ocean, and (g)–(i) sea ice from the GCMs and ERA-Interim over the southernmost latitude band 66.6°–70°N. Reprinted with permission from Svensson, G. and J. Karlsson, 2012: On the arctic wintertime climate in global climate models. *Journal of Climate* **24**: 5757-5771. DOI:10, Figure 8.

brightening over several locales. In comparison with the ERA-40 re-analyses, they infer the RCM has underestimated the real trends. The authors also conclude processes occurring beyond the model domain were responsible for these changes, as inferred by the difference between the transient and climatological runs.

Zubler *et al.* also note the cloud fraction increased during the latter part of the twentieth century, but did so more strongly in the RCM. This would impact the total sky brightening by countering the clear sky aerosol increases. However, a strong correlation between all sky changes and the North Atlantic Oscillation (NAO) also was shown. The NAO would reflect the configuration of the storm track. Lastly, the authors found (Figure 1.3.1.2) "the use of transient emissions in TRANS does not improve the temperature trends simulated with CLIM. In line with the change in cloud fraction and thus all-sky SSR (surface shortwave radiation), both RCM simulations show a similar dimming/brightening signal in temperature." This points to the dominance of natural variations in driving the surface temperature changes within the European Region. And as stated above, the RCM still over- and underestimated certain quantities. But as the authors note, some processes may not be so important that their actual representation is critical: "due to the dominating dependence of all-sky SSR on clouds, our study implies that it may not be necessary to use transient emissions in order to simulate dimming/brightening in Europe with a RCM.

The studies reviewed here suggest general circulation models of the atmosphere are seriously inadequate in the way they treat several aspects of Earth's radiative energy balance—and fail entirely to address some pertinent phenomena.

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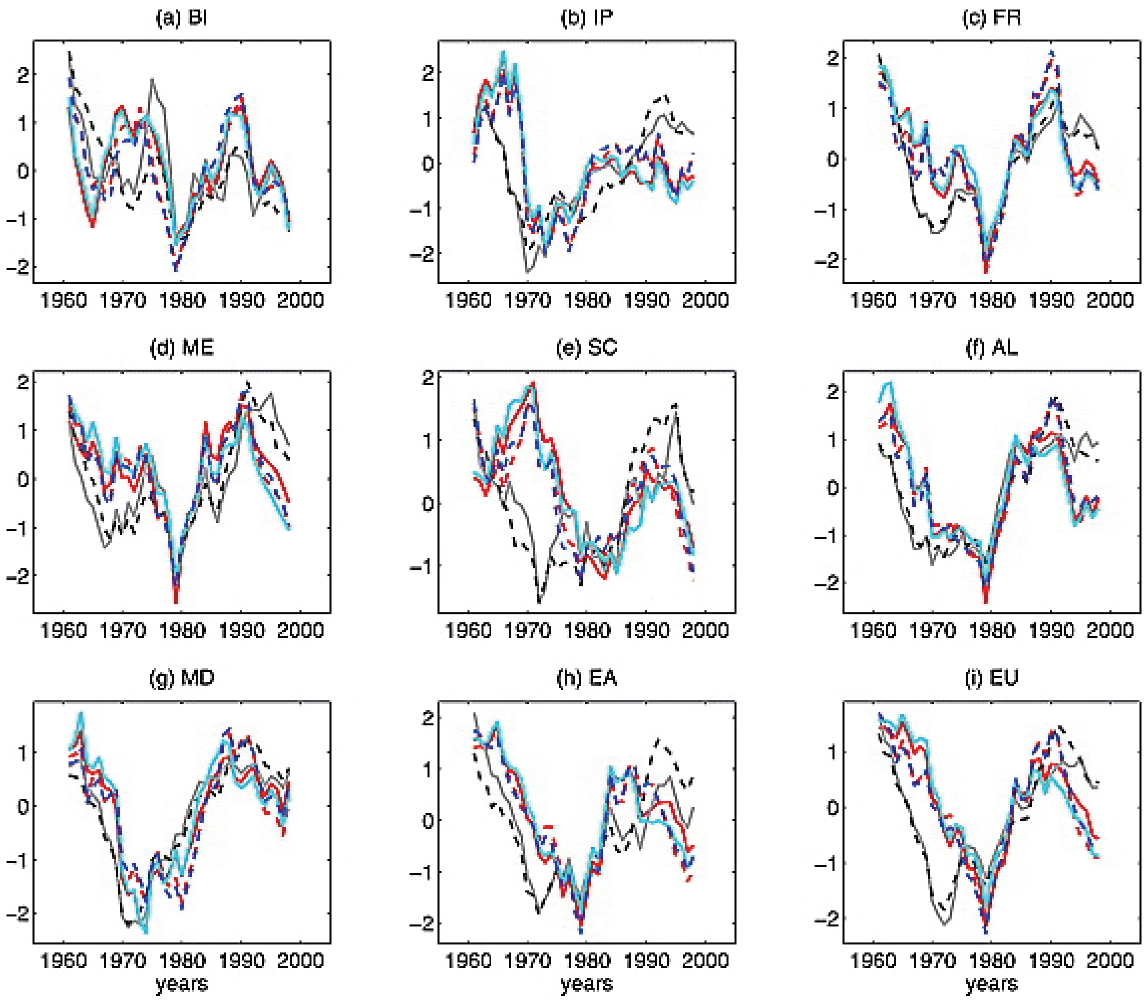

Figure 1.3.1.2. The standardized anomalies for five year running averages for various regions in Europe (see paper) for the all-sky downward surface shortwave radiation (solid black), cloud fraction multiplied by -1 (dashed black), ERA-40 (gray), transient aerosols (red), and climatological aerosols (blue). Reprinted with permission from Zubler, E.M, Folini, D., Lohmann, U., Lüthi, D., Schär, C., and M. Wild, 2011: Simulation of dimming and brightening in Europe from 1958 to 2001 using a regional climate model. *Journal of Geophysical Research* **116**: D18205, doi:10.1029/2010JD015396, Figure 5.

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1.3.2 Water Vapor

"Water vapor feedback in climate models is large and positive," note Paltridge *et al.* (2009), and "the various model representations and parameterizations of convection, turbulent transfer, and deposition of latent heat generally maintain a more-or-less constant relative humidity (i.e., an increasing specific humidity *q*) at all levels in the troposphere as the planet warms." This "increasing *q* amplifies the response of surface temperature to increasing CO_2 by a factor or 2 or more," they write. They also note the behavior of water vapor in the middle and upper levels of the troposphere dominates overall water-vapor feedback. It is at these levels where long-term measurements of the trends in water vapor concentration are least reliable.

Consequently, knowledge of how *q* (particularly the *q* of the upper levels of the troposphere) responds to atmospheric warming is of paramount importance to the task of correctly predicting the water vapor feedback and how air temperatures respond to increasing CO_2 concentrations. Paltridge *et al*. explore this important subject by determining trends in relative and specific humidity at various levels in the atmosphere based on reanalysis data of the National Centers for Environmental Prediction (NCEP) for the period 1973–2007. The three researchers report "the face-value 35-year trend in zonal-average annual-average specific humidity *q* is significantly negative at all altitudes above 850 hPa (roughly the top of the convective boundary layer) in the tropics and southern midlatitudes and at altitudes above 600 hPa in the northern midlatitudes." They conclude "negative trends in *q* as found in the NCEP data would imply that long-term water vapor feedback is negative—that it would reduce rather than amplify the response of the climate system to external forcing such as that from increasing atmospheric CO_2."

As discussed by Boehmer (2012), there is a continuing argument on this topic that boils down to two main issues. First, there is the question as to whether *in situ* balloon measurements, which suggest a negative long-term trend in upper-level *q* and hence a negative water vapor feedback, or remote sensing satellite measurements, which suggest the opposite, are correct in their measurements of *q*. The second question concerns whether short-term correlations between upper-level *q* and surface temperature can be extrapolated to deduce the existence of such a correlation over longer time scales.

Boehmer's work is critical, as the assumption that humidity will remain constant and act as an amplifier is based largely on models, which is circular reasoning. If water vapor is not an amplifier but acts as a negative feedback, the case for high climate sensitivity and alarming rates of warming is based entirely on models and not real-world data.

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1.3.3 Aerosols

1.3.3.1 Aerosols

Aerosols, whether natural or anthropogenic, can affect the weather and climate in many ways. The most obvious is by increasing the planetary albedo, which leads to a surface cooling. Aerosols also can warm the middle and upper troposphere if they absorb sunlight, possibly increasing atmospheric stability and inhibiting cloud formation. They can have indirect effects as well, by changing the nature of clouds and the formation of precipitation. And like clouds, they can only be parameterized in weather and climate models. The inadequate treatment of aerosols by GCMs represents a major limitation in the models' reliability.

Mishchenko *et al*. (2009) state "because of the global nature of aerosol climate forcings, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change," and they note "there have been parallel claims of unprecedented accuracy of aerosol retrievals with the moderate-resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR)."

If both aerosol retrieval systems are as good as they have been claimed to be, they should agree on a pixel by pixel basis as well as globally. Consequently, and noting "both instruments have been flown for many years on the same Terra platform, which provides a unique opportunity to compare fully collocated pixel-level MODIS and MISR aerosol retrievals directly," Mishchenko *et al*. decided to see how they compare in this regard by analyzing eight years of such data.

The six scientists from NASA's Goddard Institute for Space Studies report finding what they describe as "unexpected significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties." In fact, they note, "the only point on which both datasets seem to fully agree is that there may have been a weak increasing tendency in the globally averaged aerosol optical thickness (AOT) over the land and no long-term AOT tendency over the oceans." The NASA scientists state their conclusion quite succinctly: "[O]ur new results suggest that the current knowledge of the global distribution of the AOT and, especially, aerosol microphysical characteristics remains unsatisfactory." And since this knowledge is indispensable "for use in various assessments of climate and climate change," it would appear current assessments of greenhouse-gas forcing of climate made by the best models in use today may be of very little worth in describing the real world of nature.

In a contemporaneous study, Haerter *et al*. (2009) note future projections of climate "have been—for a given climate model—derived using a 'standard' set of cloud parameters that produce realistic present-day climate." However, they add, "there may exist another set of parameters that produces a similar present-day climate but is more appropriate for the description of climate change" and, "due to the high sensitivity of aerosol forcing (F) to cloud parameters, the climate projection with this set of parameters could be notably different from that obtained from the standard set of parameters, even though the present-day climate is reproduced adequately." This state of affairs suggests replication of the present-day climate is no assurance that a climate model will accurately portray Earth's climate at some future time. It is also noted this study did not examine first principles, but rather the treatment of radiational forcing, which must be parameterized.

To get a better idea of the magnitude of uncertainty associated with this conundrum, Haerter *et al*. used the ECHAM5 atmospheric general circulation model, which includes parameterizations of direct and first indirect aerosol effects, to determine what degree of variability in *F* results from reasonable uncertainties associated with seven different cloud parameters: the entrainment rate (the rate at which environmental air and cloud air mix) for shallow convection, the entrainment rate for penetrative convection, the cloud mass flux above the non-buoyancy level, the correction to asymmetry parameter for ice clouds, the inhomogeneity parameter for liquid clouds, the inhomogeneity parameter for ice clouds, and the conversion efficiency from cloud water to precipitation.

Upon completion of their analyses, the four researchers report “the uncertainty due to a single one of these parameters can be as large as 0.5 W/m^2” and “the uncertainty due to combinations of these parameters can reach more than 1 W/m^2.” As for the significance of their findings, they write, “these numbers should be compared with the sulfate aerosol forcing of -1.9 W/m^2 for the year 2000, obtained using the default values of the parameters.”

The mean sulfate aerosol forcing component of Earth’s top-of-the-atmosphere radiative budget is thus apparently not known to within anything better than ± 50 percent. In addition, Haerter *et al*. (2009) note structural uncertainties, such as “uncertainties in aerosol sources, representation of aerosols in models, parameterizations that relate aerosols and cloud droplets to simulate the indirect aerosol effect, and in cloud schemes” lead to an overall uncertainty in *F* of approximately ± 43 percent, as noted by IPCC. In reality, therefore, the current atmosphere’s aerosol radiative forcing is probably not known to anything better than ± 100%, which does not engender confidence in the ability to simulate Earth’s climate very far into the future.

In another study, Booth *et al*. (2012) note “a number of studies have provided evidence that aerosols can influence long-term changes in sea surface temperatures,” citing Mann and Emanuel (2006) and Evan *et al*. (2009), but “climate models have so far failed to reproduce these interactions,” citing Knight (2009) and Ting *et al*. (2009). They consequently note, as they phrase it, “the role of aerosols in decadal variability remains unclear.”

Booth *et al*. used the Hadley Centre Global Environmental Model version 2 (HadGEM2-ES)—a next-generation Climate Model Intercomparison Project phase 5 (CMIP5) model—to determine whether older CMIP3 models “contained the complexity necessary to represent a forced Atlantic Multidecadal Oscillation.” The five researchers were thus able to demonstrate that “aerosol emissions and periods of volcanic activity explain 76% of the simulated multidecadal variance in detrended 1860–2005 North Atlantic sea surface temperatures,” and “after 1950, simulated variability is within observational estimates,” while their estimates for 1910–1940 “capture twice the warming of previous generation models,” although they still “do not explain the entire observed trend.” Put another way, they state that “mechanistically, we find that inclusion of aerosol-cloud microphysical effects, which were included in few previous multimodel ensembles, dominates the magnitude (80%) and the spatial pattern of the total surface aerosol forcing in the North Atlantic.”

Booth *et al*. conclude their paper by noting, “one of the reasons why the role of aerosols in driving multidecadal variability has not previously been identified” is that “although all the CMIP3 models represented the direct effect of aerosols on shortwave radiation, most omitted or only partly represented the indirect aerosol effects,” citing Chang *et al*. (2011). They conclude, “we need to reassess the current attribution to natural ocean variability of a number of prominent past climate impacts linked to North Atlantic sea surface temperatures.”

Similarly, it may be that climatologists need to reassess the attribution of the post-Little Ice Age warming of the world to anthropogenic CO_2 emissions, to account for the possible warming effects of still other as-yet-unappreciated phenomena that are either “omitted or only partly represented” in current state-of-the-art climate models. Some of these phenomena may be associated with things transpiring on (or within) the Sun; other phenomena that may thwart or significantly reduce the warming effect of rising atmospheric CO_2 concentrations may be associated with a variety of biological responses of both marine and terrestrial vegetation to atmospheric CO_2 enrichment, as well as to warming itself.

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1.3.3.2 Aerosol Nuclei

Many physical processes must be approximated in GCMs using separate calculations at the grid scale, called parameterizations. In many cases this involves averaging the effect of subgrid scale processes. These processes include the existence and formation of clouds and also relate to the presence of aerosols or particulates in the air that are not considered to be part of the basic makeup the atmosphere but which strongly affect radiation fluxes. Aerosols are important because they can affect energy exchanges in the atmosphere and serve as condensation nuclei for cloud formation. Clouds have an impact on Earth's energy budget through their ability to reflect and scatter light and to absorb and emit infrared radiation. Also, cloud properties such as droplet size and concentration can influence how effectively clouds contribute to the planet's albedo.

Roesler and Penner (2010) used a microsphysical model to explore the effects of the chemical composition and size of aerosols on the concentration of cloud droplets over the United States. Using aerosol composition measurements from 1988 to 2004, the authors found aerosols influenced the size and concentration of the cloud droplets that ultimately formed in their experiments.

They also included tests varying the strength of the atmospheric vertical motions lifting air parcels, which are initially saturated, over a distance of about 300 meters in order to induce cloud formation. They found that as vertical motion increased in strength within their model, the number of cloud droplets increased. They also found that larger aerosols, though fewer in number, were more soluble as they formed cloud droplets. Smaller aerosols were more numerous but less soluble. Thus, the larger aerosols were found to be better at producing cloud droplets. The size of the aerosols depended on their chemical composition, which varied by region across the United States and by season. They found the concentrations of droplets were largest in the eastern U.S. and in the spring season.

Roesler and Penner's work makes clear that in order to model cloud forcing in a GCM, which ultimately affects the ability of the model to capture climate or climate change, the chemical composition of the condensation nuclei that form these clouds must be properly accounted. Roesler and Penner pointed out, "a global model using an empirical relationship based on regional measurements could over- or under-predict droplet concentrations when applied to other regions depending on differences in composition." GCMs must not ignore the chemical composition of aerosols—but they currently do.

In another study, Golaz *et al*. (2011) used the most recently released version of the Geophysical Fluid Dynamics Laboratory's (GFDL) Atmospheric General Circulation Model (AGCM), called AM3 (Donner *et al*., 2011), to explore the "aerosol indirect effect" (AIE) using a prognostic parameterization scheme for cloud droplet numbers. The AIE is simply the impact particulates and chemicals have on Earth's radiation budget by their influence on cloud properties. Cloud properties such as composition (ice versus water), droplet size, and droplet density are critical determinants of how clouds influence Earth's radiation budget.

Past studies have shown cloud droplet numbers are a function of aerosol types, temperature, pressure, and vertical motion (which in stratiform clouds is related to turbulence). Golaz *et al*. provided a six-year control simulation of climate after allowing one year for model equilibration. Then they changed the cloud droplet numbers in a predictive cloud scheme by reducing the turbulence in the model (experiment 1). In the second experiment an additional adjustment was made by allowing droplet formation in new clouds and preexisting clouds. The third and final experiment adjusted the vertical motion profile and the turbulence used in experiment 2.

When these experiments were run for one year, the latter two experiments produced more droplets, making the clouds more reflective and resulting in less incoming solar radiation. Golaz *et al.* note the differences among all the experiments were similar to the radiative forcing differences between today and preindustrial times. But they also observe these short-term experiments "could not be used for long-term coupled climate experiments, because the magnitude of their net top-of-the-atmosphere (TOA) radiation fluxes is unrealistically large." The model configurations were readjusted to bring energy balance in line with the reference run.

The exact formulation of model physics and assumptions used for variables such as cloud droplet numbers can have a large impact on the predicted droplet numbers. These in turn can have a relatively large impact on the net radiation budgets. Golaz *et al*. showed that, in spite of these differences, there was only a small impact on the present-day climate overall. However, when the three formulations were applied between present-day and pre-industrial climate, there was a large difference in the net radiation budgets, which can be attributed to the AEI (Figure 1.3.3.2.1). This likely would result in the model yielding "an unrealistic temperature evolution [from preindustrial to current times] compared to observations."

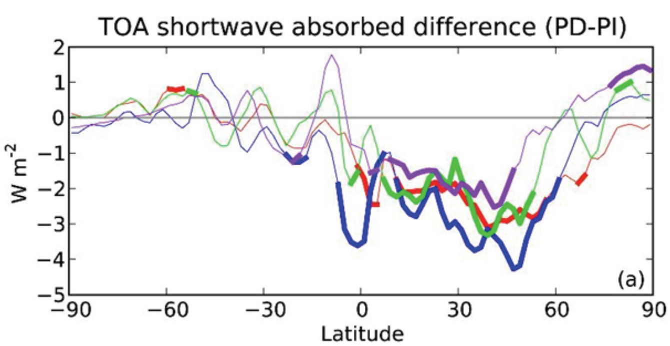

Figure 1.3.3.2.1. The zonal mean difference in the top of the atmosphere shortwave absorption between model runs with present-day conditions and preindustrial conditions using the control and three experimental parameterizations described here. The thicker lines indicate which results are statistically significant at the 95% confidence level. The red line represents the control run, and the blue, green, and purple represent the model configured for differences in cloud formation. Reprinted with permission from Golaz, J.-C., Salzmann, M., Donner, L.J., Horowitz, L.W., Ming, Y., and Zhao, M. 2011. Sensitivity of the aerosol indirect effect to subgrid variability in the cloud parameterization of the GFDL atmosphere general circulation model AM3. *Journal of Climate* **24**: 3145–3160, Figure 5a.

This paper demonstrates that uncertainty in model formulations, especially processes such as cloud parameterizations, can yield considerable uncertainty in climate projections and scenarios. The results also show the expected magnitude of the output is not known and model physics (parameterizations) must be adjusted within allowable ranges to conform with our current understanding of a process, or back towards basic conservation laws. These precautions are what many scientists have advised when looking at future climate scenarios.

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1.3.3.3 Volcanic Aerosols

The effects of volcanic eruptions on climate have been studied and are well-known. Volcanic eruptions eject particulate and aerosol materials into the stratosphere. These aerosols, primarily sulfate type, increase the albedo of the planet, resulting in less incoming solar radiation and a cooling of the lower troposphere and surface. Generally, the greater the eruption, the stronger this effect will be and the longer it will last. Volcanic eruptions whose emissions are confined to the troposphere generally have little effect on climate, as the troposphere is more efficient in scavenging out the relatively large particulates.

Volcanism is an "external" forcing to Earth's atmosphere and its occurrence is considered to be unpredictable and irregular. However, once the particulate matter and aerosols are injected into the atmosphere, it is possible to project the spread of the material using a GCM. In June 2009, the Sarychev volcano in Russia's Kamchatka Peninsula erupted explosively for approximately five days. At the time it was the second such eruption within a year. It injected 1.2 teragrams (Tg) of material into the atmosphere to an estimated height of as much as 16 km—nearly 10 miles.

Kravitz *et al.* (2011) studied measurements of the optical depth of the aerosol sulfates from this eruption and compared these with the projected output from a 20-member ensemble using a GCM, with the goal of providing suggestions for improving the model's capabilities. They used the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies Model-E, which employs a coupled atmosphere-ocean GCM with fairly coarse resolution in the horizontal (4° by 5° lat/lon) and vertical (23 layers). The model contained levels up to 80 km, necessarily including the stratosphere.

The control model run consisted of a 20-member suite globally from 2007 to 2010. In the experiment, 1.5 Tg of volcanic material was injected into the atmosphere at a point near Sarychev in 2008 of the model year. The observed aerosol measurements came from ground-based LIDARS at six locations around the world as well as satellite-based measurements that profile the aerosol concentration using scattered sunlight (Optical Spectrograph and Infrared Imaging System (OSIRIS)).

The model did a reasonably good job of spreading the volcanic material around the Northern Hemisphere, but there were some important discrepancies between the model and observations (e.g. Figure 1.3.3.3.1). For example, the model transported the material too quickly into the tropics and too slowly into the high latitudes. The authors speculate this error may indicate a need to improve the model's depiction of stratospheric circulation. Also, the model tended to remove aerosols too quickly from the atmosphere, especially in the high latitudes, which may have been an indication of model overestimation of particulate size. Note that in Figure 1.3.3.3.1, the modeled peak aerosol values occurred one month earlier than observed and then decreased in concentration too quickly.

The sensitivity of GCMs to aerosol forcing also can be assessed based on volcanic activity. The Pinatubo eruption of 1991 was very large and explosive, injecting a huge amount of sulfate aerosols into the atmosphere. The climate cooled in response, but the climate models cooled much more than the actual atmosphere, showing the models assumed strong radiative forcing (cooling) by sulfate aerosols, a result also noted by Landrum *et al.* (2013).

This is important because one of the key assumptions of the models is that human pollution, particularly in the pre-1970 period, strongly dampens out the warming that greenhouse gas emissions otherwise would have caused. For most of the period simulated, however, no data (or only fragmentary data) are available to estimate sulfate aerosol pollution. Furthermore, the forcing by any given level of aerosols is not easily measured and is usually estimated from model responses to things like volcanic activity, which is not a direct parallel to human pollution. Thus the aerosol forcing history of the twentieth century used by the IPCC is very approximate, and in fact different histories are often used by different modeling groups. Kiehl (2007) found GCMs with a larger anthropogenic forcing (more warming, which varied by a factor of 2) used a larger aerosol forcing (compensating cooling, which varied by a factor of 3). Modeling groups thus appear to have chosen an aerosol history that makes their model fit the historical record or tuned their model to accommodate the aerosol history they utilized.

Allen *et al*. (2013) found models do not capture the global dimming from the 1950s to 1980s and brightening from the 1990s, which implies "model underestimation of the observed trends is related to underestimation of aerosol radiative forcing and/or deficient aerosol emission inventories." This undermines the claim that the models are simply deduced from basic physics, and it also explains why they currently seem to be running hotter than the actual climate.

Volcanic aerosols represent yet another demonstration that climate models have a difficult time representing the impact of external and seemingly "random" forcing processes. The likely impact on surface temperatures from the Kravitz *et al*. (2011) experiment would be a bias toward warm temperatures on the time scale of months.

Driscoll *et al*. (2012) report that Stenchikov *et al*. (2006) analyzed seven models used in the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC, 2007) that "included all the models that specifically represented volcanic eruptions." The scientists found the strength and spatial pattern of the surface temperature anomalies predicted by them were not "well reproduced." Hoping to find some improvement in more recent versions of the models, Driscoll *et al*. repeated the analysis of Stenchikov *et al*. (2006), using 13 model simulations from the Coupled Model Intercomparison

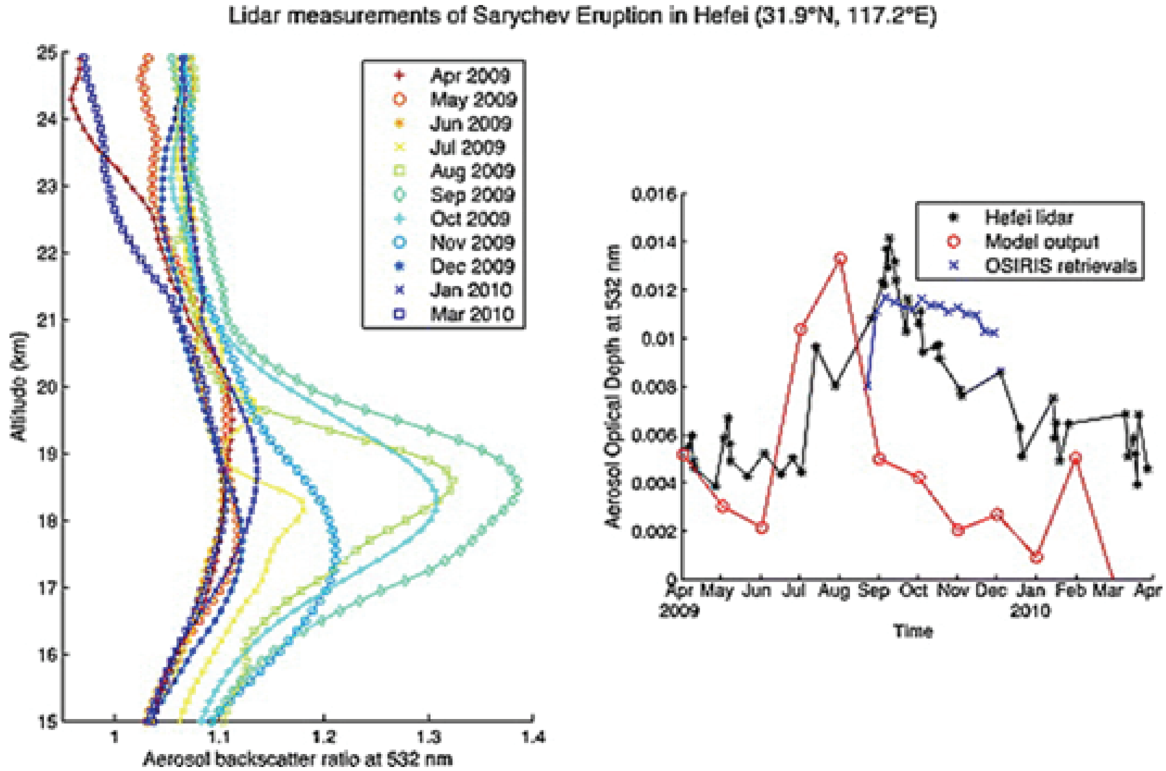

Figure 1.3.3.3.1. The LIDAR retrievals from Hefei, China as compared to model output and OSIRIS retrievals (left). The monthly averages of backscatter as a function of altitude maximizing in September 2009 (right). The integrated (15–25 km) optical depth through the stratosphere for the LIDAR data (black), zonally averaged stratospheric aerosol optical depth calculated by the model in the grid latitude containing the Hefei LIDAR (28°–32°N) (red), and OSIRIS retrievals zonally averaged over the latitude band 30°–35°N (blue). Reprinted with permission from Kravitz, B., Robock, A., Bourassa, A., Deshler, T., Wu, D., Mattis, I., Finger, F., Hoffmann, A., Ritter, C., Bitar, L., Duck, T.J., and Barnes J.E. 2011. Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. *Journal of Geophysical Research-Atmospheres* **116**: D18211, doi:10.1029/ 2010JD015501, Figure 11.

Project phase 5 (CMIP5)—an overview of which is given by Taylor *et al*. (2011)—while focusing their analysis on the regional impacts of the largest volcanic eruptions on the Northern Hemisphere (NH) large-scale circulation during the winter season.

According to the five researchers, "the models generally fail to capture the NH dynamical response following eruptions." More specifically, they state the models "do not sufficiently simulate the observed post-volcanic strengthened NH polar vortex, positive North Atlantic Oscillation, or NH Eurasian warming pattern, and they tend to overestimate the cooling in the tropical troposphere." They also note "none of the models simulate a sufficiently strong reduction in the geopotential height at high latitudes," and correspondingly, "the mean sea level pressure fields and temperature fields show major differences with respect to the observed anomalies." In addition, they find "all models show considerably less variability in high-latitude stratospheric winds than observed," and "none of the models tested have a Quasi-Biennial Oscillation in them."

Given such "substantially different dynamics between the models," Driscoll *et al*. report they had "hoped to find at least one model simulation that was dynamically consistent with observations, showing improvement since Stenchikov *et al*. (2006)." But "disappointingly," they found "despite relatively consistent post volcanic radiative changes, none of the models manage to simulate a sufficiently strong dynamical response." They say their study "confirms previous similar evaluations and raises concern for the ability of current climate models to simulate the response of a major mode of global circulation variability to external forcings," noting "this is also of concern for the accuracy of geoengineering modeling studies that assess the atmospheric response to stratosphere-injected particles."

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1.3.4 Clouds

Correctly parameterizing the influence of clouds on climate is an elusive goal the creators of atmospheric GCMs have yet to achieve. One major reason for their lack of success has to do with inadequate model resolution on vertical and horizontal space scales. Lack of resolution forces modelers to parameterize the ensemble large-scale effects of processes that occur on smaller scales than the models are capable of handling. This is particularly true of physical processes such as cloud formation and cloud-radiation interactions. Several studies suggest older model parameterizations did not succeed in this regard (Groisman *et al*., 2000), and subsequent studies, as discussed in this section, suggest they still are not succeeding. The lack of success may not be due entirely to inadequate model resolution: If cloud processes have not been adequately and properly quantified, not even the highest resolution will bring success.

Lane *et al*. (2000) evaluated the sensitivities of the cloud-radiation parameterizations utilized in contemporary GCMs to changes in vertical model resolution, varying the latter from 16 to 60 layers in increments of four and comparing the results to observed values. This effort revealed cloud fraction varied by approximately 10 percent over the range of resolutions tested, which corresponded to about 20 percent of the observed cloud cover fraction. Similarly, outgoing longwave radiation varied by 10 to 20 Wm^{-2} as model vertical resolution was varied, amounting to approximately 5 to 10 percent of observed values, and incoming solar radiation experienced similar significant variations across the range of resolutions tested. The model results did not converge, even at a resolution of 60 layers.

In an analysis of the multiple roles played by cloud microphysical processes in determining tropical climate, Grabowski (2000) found much the same thing, noting there were serious problems of computer models failing to correctly incorporate cloud microphysics. These observations led him to conclude "it is unlikely that traditional convection parameterizations can be used to address this fundamental question in an effective way." He also became convinced that "classical convection parameterizations do not include realistic elements of cloud physics and they represent interactions among cloud physics, radiative processes, and surface processes within a very limited scope." Consequently, he added, "model results must be treated as qualitative rather than quantitative."

Reaching similar conclusions were Gordon *et al*. (2000), who determined many GCMs of the late 1990s tended to under-predict the presence of subtropical marine stratocumulus clouds and failed to simulate the seasonal cycle of clouds. These deficiencies are important because these particular clouds exert a major cooling influence on the surface temperatures of the sea below them. In the situation investigated by Gordon and his colleagues, the removal of the low clouds, as occurred in the normal application of their model, led to sea surface temperature increases on the order of 5.5°C.

Further condemnation of turn-of-the-century model treatments of clouds came from Harries (2000), who write our knowledge of high cirrus clouds is very poor and "we could easily have uncertainties of many tens of Wm^{-2} in our description of the radiative effect of such clouds, and how these properties may change under climate forcing."

Lindzen *et al*. (2001) analyzed cloud cover and sea surface temperature (SST) data over a large portion of the Pacific Ocean, finding a strong inverse relationship between upper-level cloud area and mean SST, such that the area of cirrus cloud coverage normalized by a measure of the area of cumulus coverage decreased by about 22 percent for each degree C increase in cloudy region SST. Essentially, as the researchers describe it, "the cloudy-moist region appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." The sensitivity of this negative feedback was calculated by Lindzen *et al*. to be substantial. They estimate it would "more than cancel all the positive feedbacks in the more sensitive current climate models" being used to predict the consequences of projected increases in atmospheric CO_2 concentration.

Lindzen's conclusions did not go uncontested, and Hartmann and Michelsen (2002) quickly claimed the correlation noted by Lindzen *et al*. resulted from variations in subtropical clouds not physically connected to deep convection near the equator, and it was thus "unreasonable to interpret these changes as evidence that deep tropical convective anvils contract in response to SST increases." Fu *et al.* (2002) also chipped away at the adaptive infrared iris concept, arguing "the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive," while also claiming to show water vapor and low cloud effects were overestimated by Lindzen *et al*. by at least 60 percent and 33 percent, respectively. As a result, Fu *et al.* obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al.'s* much larger negative feedback factor of -0.45 to -1.03.

In a contemporaneously published reply to this critique, Chou *et al*. (2002) state Fu *et al*.'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect." Since "thin cirrus are widespread in the tropics and ... low boundary clouds are optically thick, the cloud albedo calculated by [Fu *et al*.] is too large for cirrus clouds and too small for boundary layer clouds," they write, so "the near-zero contrast in cloud albedos derived by [Fu *et al*.] has the effect of underestimating the iris effect." In the end, Chou *et al*. agreed Lindzen *et al*. "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al*.]."

Grassl (2000), in a review of the then-current status of the climate-modeling enterprise two years before the infrared iris effect debate emerged, noted changes in many climate-related phenomena, including cloud optical and precipitation properties caused by changes in the spectrum of cloud condensation nuclei, were insufficiently well known to provide useful insights into future conditions. In light of this knowledge gap, he recommended "we must continuously evaluate and improve the GCMs we use," although he acknowledges contemporary climate model results were already being "used by many decision-makers, including governments."

Some may consider what is currently known about clouds to be sufficient for predictive purposes, but the host of questions posed by Grassl—for which definitive answers are still lacking—demonstrates this assumption is erroneous. As but a single example, Charlson *et al*. (1987) describe a negative feedback process that links biologically produced dimethyl sulfide (DMS) in the oceans with climate. (See Chapter 2 of this volume for a more complete discussion of this topic.) This hypothesis holds that the global radiation balance is significantly influenced by the albedo of marine stratus clouds and that the albedo of these clouds is a function of cloud droplet concentration, which is dependent upon the availability of condensation nuclei that have their origin in the flux of DMS from the world's oceans to the atmosphere.

Acknowledging that the roles played by DMS oxidation products in the context described above are "diverse and complex" and in many instances "not well understood," Ayers and Gillett (2000) summarized empirical evidence, derived from data collected at Cape Grim, Tasmania, and from reports of other pertinent studies in the peer-reviewed scientific literature, supporting Charlson *et al*.'s (1987) hypothesis. Ayers and Gillett found the "major links in the feedback chain proposed by Charlson *et al.* (1987) have a sound physical basis" and there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

The empirical evidence analyzed by Ayers and

Gillett highlights an important suite of negative feedback processes that act in opposition to model-predicted CO_2-induced global warming over the world's oceans. These processes are not fully incorporated into even the best of the current climate models, nor are analogous phenomena that occur over land included in them, such as those discussed by Idso (1990).

Further to this point, O'Dowd *et al*. (2004) measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms at various times of the year. They found in the winter, when biological activity was at its lowest, the organic fraction of the sub-micrometer aerosol mass was about 15 percent. During the spring through autumn, however, when biological activity was high, "the organic fraction dominates and contributes 63 percent to the sub-micrometer aerosol mass (about 45 percent is water-insoluble and about 18 percent water-soluble)," they write. Based on these findings, they performed model simulations that indicated the marine-derived organic matter "can enhance the cloud droplet concentration by 15 percent to more than 100 percent and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota."

O'Dowd *et al.* (2004) state their findings "completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models," or as they note elsewhere in their paper, "an important source of organic matter from the ocean is omitted from current climate-modeling predictions and should be taken into account."

Another perspective on the cloud-climate conundrum is provided by Randall *et al.* (2003), who state at the outset of their review of the subject that "the representation of cloud processes in global atmospheric models has been recognized for decades as the source of much of the uncertainty surrounding predictions of climate variability." They report that "despite the best efforts of [the climate modeling] community … the problem remains largely unsolved" and note, "at the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future."

Randall *et al.* declare "clouds are complicated," highlighting what they call the "appalling complexity" of the cloud parameterization situation. They also state "our understanding of the interactions of the hot towers [of cumulus convection] with the global circulation is still in a fairly primitive state," and not knowing all that much about what goes up, it's not surprising we also don't know much about what comes down, as they report "downdrafts are either not parameterized or crudely parameterized in large-scale models." It also should be noted Riehl and Malkus (1958), in an analysis of the equatorial trough region, could not achieve closure of their large-scale energy budgets without resorting to significant vertical exchanges by way of the cumulonimbus downdrafts.

With respect to stratiform clouds, the situation is no better, as their parameterizations are described by Randall *et al.* as "very rough caricatures of reality." As for interactions between convective and stratiform clouds, during the 1970s and '80s, Randall *et al.* report "cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds." They reported the concept of detrainment was "somewhat murky" and the conditions that trigger detrainment were "imperfectly understood." "At this time," as they put it, "no existing GCM includes a satisfactory parameterization of the effects of mesoscale cloud circulations."

Randall *et al*. additionally state "the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert," but they report only a few GCMs have even attempted to do so. Why? Because, as they continue, "the cloud parameterization problem is overwhelmingly complicated" and "cloud parameterization developers," as they call them, are still "struggling to identify the most important processes on the basis of woefully incomplete observations." They add, "there is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard." The four scientists conclude, "a sober assessment suggests that with current approaches the cloud parameterization problem will not be 'solved' in any of our lifetimes."

To show the basis for this conclusion is robust and cannot be said to rest on the less-than-enthusiastic remarks of a handful of exasperated climate modelers, additional studies on the subject have been published subsequent to Randall *et al.,* any of which could have readily refuted their assessment of the situation if they thought it was appropriate.

Siebesma *et al.* (2004), for example, report "simulations with nine large-scale models [were] carried out for June/July/August 1998 and the quality of the results [was] assessed along a cross-section in the subtropical and tropical North Pacific ranging from (235°E, 35°N) to (187.5°E, 1°S)," in order to "document the performance quality of state-of-the-art GCMs in modeling the first-order characteristics of subtropical and tropical cloud systems." The main conclusions of this study, according to the authors are: "(1) almost all models strongly under predicted both cloud cover and cloud amount in the stratocumulus regions while (2) the situation is opposite in the trade-wind region and the tropics where cloud cover and cloud amount are over predicted by most models." They report "these deficiencies result in an over prediction of the downwelling surface short-wave radiation of typically 60 Wm^{-2} in the stratocumulus regimes and a similar under prediction of 60 Wm^{-2} in the trade-wind regions and in the intertropical convergence zone (ITCZ)," and these discrepancies are to be compared with a radiative forcing of only a couple of Wm^{-2} for a 300 ppm increase in the atmosphere's CO_2 concentration. In addition, they note "similar biases for the short-wave radiation were found at the top of the atmosphere, while discrepancies in the outgoing long-wave radiation are most pronounced in the ITCZ."

The 17 scientists hailing from nine different countries who comprised Siebesma *et al.* also found "the representation of clouds in general-circulation models remains one of the most important as yet unresolved issues in atmospheric modeling." This is partially due, they continue, "to the overwhelming variety of clouds observed in the atmosphere, but even more so due to the large number of physical processes governing cloud formation and evolution as well as the great complexity of their interactions." Hence, they conclude that through repeated critical evaluations of the type they conducted, "the scientific community will be forced to develop further physically sound parameterizations that ultimately result in models that are capable of simulating our climate system with increasing realism."

In their effort to assess the status of state-of-the-art climate models in simulating cloud-related processes, Zhang *et al*. (2005) compared basic cloud climatologies derived from ten atmospheric GCMs with satellite measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) and the Clouds and Earth's Radiant Energy System (CERES) program. ISCCP data were available for 1983–2001, and data from the CERES program were available for the winter months of 2001 and 2002 and for the summer months of 2000 and 2001. The purpose of their analysis was twofold: to assess the current status of climate models in simulating clouds so that future progress can be measured more objectively, and to reveal serious deficiencies in the models so as to improve them.

The work of 20 climate modelers involved in this exercise revealed a long list of major model imperfections. First, Zhang *et al*. report a fourfold difference in high clouds among the models, and that the majority of the models simulated only 30 to 40 percent of the observed middle clouds, with some models simulating less than a quarter of observed middle clouds. For low clouds, they report half the models underestimated them, such that the grand mean of low clouds from all models was only 70 to 80 percent of what was observed. Furthermore, when stratified in optical thickness ranges, the majority of the models simulated optically thick clouds more than twice as frequently as was found to be the case in the satellite observations, and the grand mean of all models simulated about 80 percent of optically intermediate clouds and 60 percent of optically thin clouds. In the case of individual cloud types, the group of researchers note "differences of seasonal amplitudes among the models and satellite measurements can reach several hundred percent." Zhang *et al.* (2005) conclude "much more needs to be done to fully understand the physical causes of model cloud biases presented here and to improve the models."

L'Ecuyer and Stephens (2007) used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period from January 1998 through December 1999 in order to evaluate the sensitivity of atmospheric heating—and the factors that modify it—to changes in east-west sea surface temperature gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere that were utilized in the IPCC's most recent *Fourth Assessment Report*. This protocol, in their words, "provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures."

Results indicate "a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event." They also found "the inter-model variability in the responses of precipitation, total heating, and vertical motion is often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO." In addition, they report "many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds." As a result of these much-less-than-adequate findings, the two researchers from Colorado State University's Department of Atmospheric Science conclude "deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models," and these deficiencies "cannot be ignored when interpreting their predictions of future climate."

In a contemporaneous publication, this one in the *Journal of the Atmospheric Sciences*, Zhou *et al*. (2007) state "clouds and precipitation play key roles in linking the Earth's energy cycle and water cycles," noting "the sensitivity of deep convective cloud systems and their associated precipitation efficiency in response to climate change are key factors in predicting the future climate." They also report cloud-resolving models, or CRMs, "have become one of the primary tools to develop the physical parameterizations of moist and other subgrid-scale processes in global circulation and climate models," and CRMs could someday be used in place of traditional cloud parameterizations in such models.

In this regard, the authors note "CRMs still need parameterizations on scales smaller than their grid resolutions and have many known and unknown deficiencies." To help stimulate progress in these areas, the nine scientists compared the cloud and precipitation properties observed from CERES and Tropical Rainfall Measuring Mission (TRMM) instruments against simulations obtained from the three-dimensional Goddard Cumulus Ensemble (GCE) model during the South China Sea Monsoon Experiment (SCSMEX) field campaign of 18 May–18 June 1998.

Zhou *et al*. report: (1) "the model has much higher domain-averaged OLR (outgoing longwave radiation) due to smaller total cloud fraction"; (2) "the model has a more skewed distribution of OLR and effective cloud top than CERES observations, indicating that the model's cloud field is insufficient in area extent"; (3) "the GCE is ... not very efficient in stratiform rain conditions because of the large amounts of slowly falling snow and graupel that are simulated"; and (4) "large differences between model and observations exist in the rain spectrum and the vertical hydrometeor profiles that contribute to the associated cloud field."

One year later, a study by Spencer and Braswell (2008) observed "our understanding of how sensitive the climate system is to radiative perturbations has been limited by large uncertainties regarding how clouds and other elements of the climate system feedback to surface temperature change (e.g., Webster and Stephens, 1984; Cess *et al.,* 1990; Senior and Mitchell, 1993; Stephens, 2005; Soden and Held, 2006; Spencer *et al.,* 2007)." The two scientists from the Earth System Science Center at the University of Alabama in Huntsville, Alabama then point out computer models typically assume that if the causes of internal sources of variability (X terms) are uncorrelated to surface temperature changes, then they will not affect the accuracy of regressions used to estimate the relationship between radiative flux changes and surface temperature (T). But "while it is true that the processes that cause the X terms are, by [Forster and Gregory (2006)] definition, uncorrelated to T, the response of T to those forcings cannot be uncorrelated to T—for the simple reason that it is a radiative forcing that causes changes in T." They then ask, "to what degree could nonfeedback sources of radiative flux variability contaminate feedback estimates?"

In an attempt to answer this question, Spencer and Braswell used a "very simple time-dependent model of temperature deviations away from an equilibrium state" to estimate the effects of "daily random fluctuations in an unknown nonfeedback radiative source term N, such as those one might expect from stochastic variations in low cloud cover." Repeated runs of the model found the diagnosed feedback departed from the true, expected feedback value of the radiative forcing, with the difference increasing as the amount of nonfeedback radiative flux noise was increased. "It is significant," the authors write, "that all model errors for runs consistent with satellite-observed variability are in the direction of positive feedback, raising the possibility that current observational estimates of cloud feedback are biased in the positive direction." In other words, as the authors report in their abstract, "current observational diagnoses of cloud feedback—and possibly other feedbacks—could be significantly biased in the positive direction."

Writing as background for their work, Zhang *et al.* (2010) state different representations of clouds and their feedback processes in GCMs have been identified as major sources of differences in model climate sensitivities, noting "contemporary GCMs cannot resolve clouds and highly simplified parameterizations are used to represent the interactions between clouds and radiation." In conducting their own study of the subject, therefore, they combine cloud profiling radar data from the CloudSat satellite with lidar data from the CALIPSO satellite to obtain 3D profiles of clouds and precipitation regimes across the tropics. Some of these profiles corresponded to well-known weather features, such as low clouds, thin cirrus, cirrus anvils, etc., and they were compared to output obtained from the Community Atmosphere Model version 3 (CAM3.1).

This analysis revealed the model "overestimates the area coverage of high clouds and underestimates the area coverage of low clouds in subsidence regions." Zhang *et al*. found particularly striking "the model overestimate of the occurrence frequency of deep convection and the complete absence of cirrus anvils," plus the fact that "the modeled clouds are too reflective in all regimes."

Since incoming and outgoing radiation are strongly affected by the 3D spatial pattern of clouds of various types, a model that gets the "right" current global temperature with the wrong pattern of clouds must have errors in its radiation and/or heat transfer parameterizations. In addition, the manner in which future climate scenarios achieve amplification of the direct radiative effect of increased greenhouse gases (the assumed positive feedback) is also not likely to be correct if the 3D pattern of simulated clouds is as far off as shown in this study. What is more, the pattern of clouds also reflects convective processes that distribute heat and water vapor in the atmosphere, and the results of Zhang *et al.* point to deficiencies in the handling of this aspect of atmospheric dynamics as well. Climate modelers' claims of physical realism in their models are not supported by detailed comparisons with the real world, and the basic radiative physics they employ, as parameterized at the grid scale, is probably faulty.

Shifting to a different aspect of the topic, climate modelers have long struggled to adequately represent the sensitivity of convective cloud systems to tropospheric humidity in their mathematical representations of Earth's climate system. Del Genio (2012) reviewed the rate of progress in this important endeavor in a paper published in the journal *Surveys in Geophysics*. The U.S. National Aeronautics and Space Administration scientist—stationed at the Goddard Institute for Space Studies in New York—found a number of important problems that have yet to be adequately resolved. He notes, for example, that many parameterizations of convective cloud variability "are not sufficiently sensitive to variations in tropospheric humidity." That "lack of sensitivity," as he describes it, "can be traced in part to underestimated entrainment of environmental air into rising convective clouds and insufficient evaporation of rain into the environment." As a result of these deficiencies, he notes, "the parameterizations produce deep convection too easily while stabilizing the environment too quickly to allow the effects of convective mesoscale organization to occur."

Del Genio does note "recent versions of some models have increased their sensitivity to tropospheric humidity and improved some aspects of their variability," but he says "a parameterization of mesoscale organization is still absent from most models," and "adequately portraying convection in all its realizations remains a difficult problem."

On another note, Del Genio writes, "to date, metrics for model evaluation have focused almost exclusively on time mean two-dimensional spatial distributions of easily observed parameters," and he indicates "it has become clear that such metrics have no predictive value for climate feedbacks and climate sensitivity (e.g., Collins *et al*., 2011)," while adding those metrics "are also probably not helpful for assessing most other important features of future climate projections, because temporal variability gives greater insight into the physical processes at work."

Del Genio concludes, "given the insensitivity of these models to tropospheric humidity and their failure to simulate the Madden-Julian Oscillation and diurnal cycle, ... it seems unlikely that it will ever be possible to establish a general set of metrics that can be used to anoint one subset of models as our most reliable indicators of all aspects of climate change."

In another study, Cesana and Chepfer (2012) compare the most recent cloud representations of five of the climate models involved in the Coupled Model Intercomparison Project Phase 5 (CMIP5) effort described by Taylor *et al*. (2012) with real-world satellite-derived observations obtained from the GCM-Oriented CALIPSO Cloud Product (GOCCP), described by Chepfer *et al*. (2010). According to Cesana and Chepfer, the results indicated: (1) “low- and mid-level clouds are underestimated by all the models (except in the Arctic),” (2) “high altitude cloud cover is overestimated by some models,” (3) “some models shift the altitude of the clouds along the ITCZ by 2 km (higher or lower) compared to observations,” (4) “the models hardly reproduce the cloud free subsidence branch of the Hadley cells,” (5) “the high-level cloud cover is often too large,” (6) “in the tropics, the low-level cloud cover (29% in CALIPSO-GOCCP) is underestimated by all models in subsidence regions (16% to 25%),” and (7) “the pronounced seasonal cycle observed in low-level Arctic clouds is hardly simulated by some models.”

Also writing in 2012, Li *et al*. (2012) state “representing clouds and cloud climate feedback in global climate models (GCMs) remains a pressing challenge,” but one that must be overcome in order “to reduce and quantify uncertainties associated with climate change projections.” Two of the primary parameters that must be accurately modeled in this regard are cloud ice water content (CIWC) and cloud ice water path (CIWP).

Li *et al*. performed, in their words, “an observationally based evaluation of the cloud ice water content and path of present-day GCMs, notably 20th century CMIP5 simulations,” after which they compared the results to two recent reanalyses. They used “three different CloudSat + CALIPSO ice water products and two methods to remove the contribution from the convective core ice mass and/or precipitating cloud hydrometeors with variable sizes and falling speeds so that a robust observational estimate can be obtained for model evaluations.”

The 11 U.S. scientists report, “for annual mean CIWP, there are factors of 2–10 in the differences between observations and models for a majority of the GCMs and for a number of regions,” and “systematic biases in CIWC vertical structure occur below the mid-troposphere where the models overestimate CIWC.” They ultimately conclude “neither the CMIP5 ensemble mean nor any individual model performs particularly well,” adding, “there are still a number of models that exhibit very large biases,” “despite the availability of relevant observations.” Even in cases where “the models may be providing roughly the correct radiative energy budget,” they state “many are accomplishing it by means of unrealistic cloud characteristics of cloud ice mass at a minimum, which in turn likely indicates unrealistic cloud particle sizes and cloud cover.” Li *et al*. conclude “cloud feedback will undoubtedly still represent a key uncertainty in [even] the next IPCC assessment report.”

Cesana *et al*. (2012) state “low-level clouds frequently occur in the Arctic and exert a large influence on Arctic surface radiative fluxes and Arctic climate feedbacks,” noting that during winter, in particular, surface net longwave radiation ($F_{LW,NET}$) has a bimodal distribution, with extremes that have been termed “radiatively clear” and “radiatively opaque.” They note Arctic ice clouds “tend to have small optical depths and a weak influence on $F_{LW,NET}$,” which explains the “radiatively clear” condition, whereas Arctic liquid-containing clouds “generally have large optical depths and a dominant influence on $F_{LW,NET}$ (Shupe and Intrieri, 2004),” which explains the “radiatively opaque” condition, as discussed by Doyle *et al*. (2011).

Against this backdrop, Cesana *et al*. employed real-world Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data to document cloud phases over the Arctic basin (60–82°N) during the five-year period 2006–2011, after which they used the results they obtained “to evaluate the influence of Arctic cloud phase on Arctic cloud radiative flux biases in climate models.” The five researchers report their evaluation of climate models participating in the most recent Coupled Model Inter-comparison Project (Taylor *et al*., 2012) revealed “most climate models are not accurately representing the bimodality of $F_{LW,NET}$ in non-summer seasons.” Even when advanced microphysical schemes that predict cloud phase have been used, such as those currently employed in the fifth version of the Community Atmosphere Model (CAM5, Neale *et al*., 2010), “insufficient liquid water was predicted.”

Cesana *et al*. conclude “the simple prescribed relationships between cloud phase and temperature that have historically been used in climate models are incapable of reproducing the Arctic cloud phase observations described here,” which must inevitably lead to similarly inaccurate values of “Arctic surface radiative fluxes and Arctic climate feedbacks” when employed in current climate models.

Also focusing on low-level clouds were Nam *et al*. (2012), who write the response of low-level clouds has long been identified as “a key source of uncertainty for model cloud feedbacks under climate change,” citing the work of Bony and Dufresne (2005), Webb *et al*. (2006), Wyant *et al*. (2006), and

Medeiros *et al*. (2008). They state "the ability of climate models to simulate low-clouds and their radiative properties" plays a large role in assessing "our confidence in climate projections." Nam *et al*. analyzed "outputs from multiple climate models participating in the Fifth phase of the Coupled Model Intercomparison Project (CMIP5) using the Cloud Feedback Model Intercomparison Project Observations Simulator Package (COSP), and compared them with different satellite data sets," including "CALIPSO lidar observations, PARASOL mono-directional reflectances, and CERES radiative fluxes at the top of the atmosphere."

The comparison revealed "the current generation of climate models still experiences difficulties in predicting the low-cloud cover and its radiative effects." In particular, they report the models: (1) "under-estimate low-cloud cover in the tropics," (2) "over-estimate optical thickness of low-clouds, particularly in shallow cumulus regimes," (3) "poorly represent the dependence of the low-cloud vertical structure on large-scale environmental conditions," and (4) "predict stratocumulus-type of clouds in regimes where shallow cumulus cloud-types should prevail." However, they say "the impact of these biases on the Earth's radiation budget ... is reduced by compensating errors," including "the tendency of models to under-estimate the low-cloud cover and to over-estimate the occurrence of mid- and high-clouds above low-clouds."

Convective-type clouds and precipitation, especially when occurring over land areas, in the tropics, or during the warm season, have a strong diurnal cycle in phase with solar heating. People living in coastal regions are familiar with the diurnal cycle via the sea-breeze phenomenon. Unfortunately, models have difficulty representing the diurnal component of convection. Stratton and Stirling (2012) devised a better way to represent this phenomenon in an atmospheric general circulation model. In particular, they improved the rate at which environmental air and cloud air mix (entrainment). They also revised the mass flux over land in order to improve the timing and strength of convection influenced by diurnal heating.

In order to test the impact of the changes made to the diurnal convection scheme on the precipitation climatology of a model, Stratton and Stirling used a GCM with a horizontal resolution of less than two degrees in latitude and longitude and ran two ten-year simulations. The first was a control run with the model as it was provided to them. Then a ten-year run was performed with the new convective parameterizations added. Results were compared with observed precipitation, as derived from output provided by the Tropical Rainfall Measurement Mission (TRMM) satellite.

According to the authors, the control run (Figure 1.3.4.1) "tends to lack precipitation over India and have too much precipitation over tropical land in Africa and in South America. The new run has generally reduced the precipitation over tropical land, tending to improve agreement with CMAP" (CMAP is an acronym for the observations). In the mid-latitudes though, there were regions (e.g., western Russia) where the new parameterization improved the model results, but other places where the new parameterization was worse (e.g., Europe). The results also did not noticeably alter the general circulation.

Stratton and Stirling improved the attendant physics associated with convection and in general improved the climatological representation of precipitation. But there were still differences in comparison with observed precipitation. In some regions, the new convective scheme performance was not as good. Improvement was not uniform, even though the model was overall closer to reality.

The new parameterizations may have done a good job of representing precipitation over short time-scales, but over longer time-scales it still did not represent the climatology of precipitation very well.

Ahlgrimm and Forbes (2012) investigated an irradiance bias in the European Centre for Medium Range Forecasting (ECMWF) GCM, focusing on the Southern Great Plains of the USA. This GCM was built to generate daily weather predictions. In one experiment, the authors compared measured radiation daily in 2004–2009 from the Atmospheric Radiation Measurement Site (ARM) in the Southern Great Plains (SGP) (Figure 1.3.4.2). In the second, they compared the ECMWF model output to observations of clouds, radiation, and the state of the atmosphere archived as the Climate Modelling Best Estimate product from 1997–2009. Ahlgrimm and Forbes selected 146 days when fair weather cumulus clouds dominated the Southern Great Plains. They compared these to the same days run using the ECMWF model initialized the day before and using the 18–42 hour forecasts.

The results indicate the mean model radiative bias compared to the observed product was approximately 23 W m^{-2}. When the authors looked at the fair weather cumulus regime and studied the bias over the

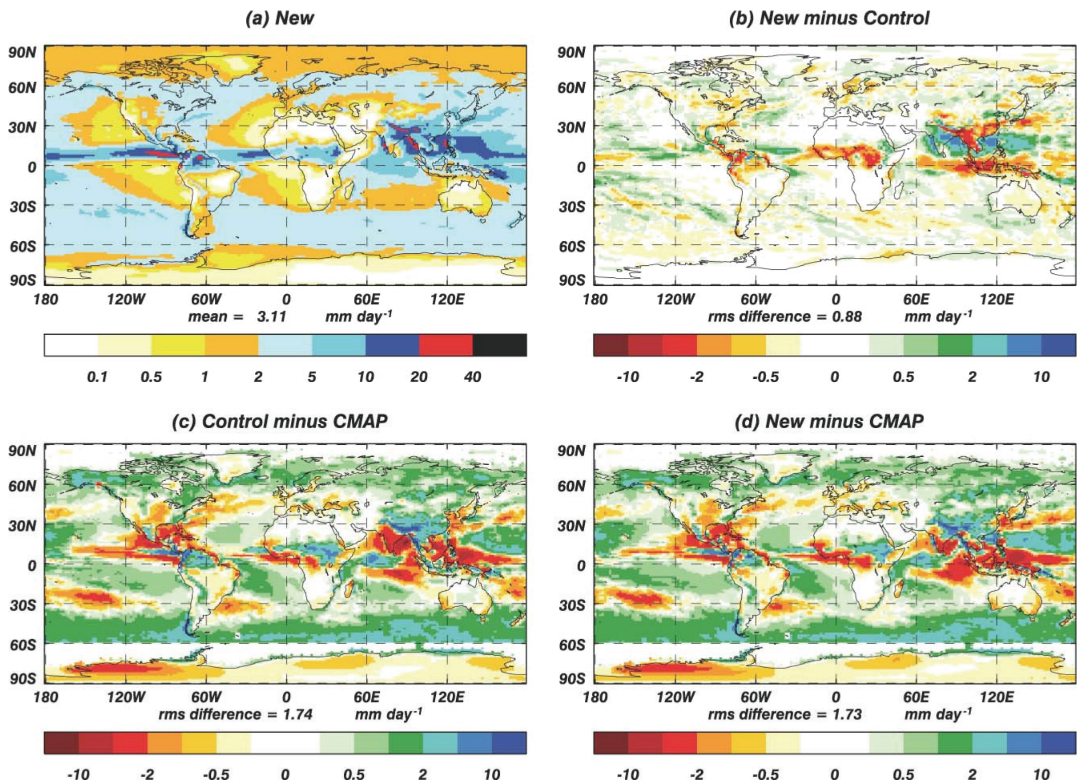

Figure 1.3.4.1. The mean summer season precipitation for (a) new convective climatology, (b) new run minus the control, (c) control minus CMAP (observations), (d) new run minus CMAP. Reprinted with permission from Stratton, R.A. and Stirling, A.J. 2012. Improving the diurnal cycle of convection in GCMs. *Quarterly Journal of the Royal Meteorological Society* **138**: 1121–1134, Figure 3.

course of a day, they found the bias in this regime was weak. This means the parameterizations for fair weather convective cloudiness were largely successful. When the authors attempted to classify clouds, they found the deep clouds (convective), thick mid-level clouds, and low clouds as a group accounted for more than 50 percent of the bias. As there was no way to account for high clouds and other phenomena, the remaining bias was simply referred to as "residual." They also demonstrated refinements in the cloud liquid water content and distributions could improve these parameterizations.

Lastly, Alhgrimm and Forbes showed the biases are largest when the observations were cloudy and the model clear, or when the observations were overcast and the model produced broken skies. All other categories showed small biases that largely cancelled each other out. The two researchers conclude, "it will be possible to carry out targeted sensitivity studies to improve cloud occurrence and radiative properties by examining the formulation of the shallow convection trigger, mass transport, and cloud microphysical properties." If there is a net positive bias in shortwave reaching the surface, it will result in the overestimation of temperatures in the two situations described above and overall. If these parameterizations, or others that produce warm biases, are used in climate models, the impact on climate scenarios would be a net surface warming.

Grodsky *et al*. (2012) point out "the seasonal climate of the tropical Atlantic Ocean is notoriously difficult to simulate accurately in coupled models," noting a long history of studies, including those of Zeng *et al*. (1996), Davey *et al*. (2002), Deser *et al*. (2006), Chang *et al*. (2007), and Richter and Xie (2008), "have linked the ultimate causes of the persistent model biases to problems in simulating winds and clouds by the atmospheric model component." In an effort designed to "revisit" this unsolved problem, Grodsky *et al*. utilized the Community Climate System Model, version 4 (CCSM4; Gent *et al*., 2011), a coupled climate model that simultaneously simulates Earth's atmosphere, ocean, land surface, and sea ice processes. They did

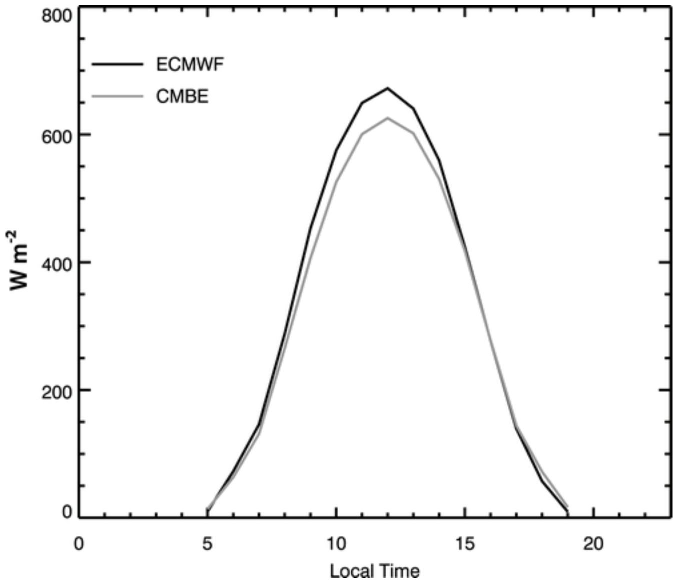

Figure 1.3.4.2. The multiyear (2004–09) all-sky diurnal composite of surface irradiance. The black line is the ECMWF model, and the grey line is the observations from the CMBE product. Only daytime samples (modelled short wave down exceeding 1 W m^{-2}) with good-quality coincident observations are included. Reprinted with permission from Ahlgrimm, M. and Forbes, R. 2012. The impact of low clouds on surface shortwave radiation in the ECMWF model. *Monthly Weather Review* **140**: 3783–3794, Figure 1.

so by comparing twentieth century runs forced by time-varying solar output, greenhouse gas, and volcanic and other aerosol concentrations for the period 1850–2005 with observed (real world) monthly variability computed from observational analyses during the 26-year period 1980–2005.

The four researchers report finding (1) the "atmospheric component of CCSM4 has abnormally intense surface subtropical high pressure systems and abnormally low polar low pressure systems," (2) "in the tropics and subtropics, the trade wind winds are 1-2 m/sec too strong [and] latent heat loss is too large," (3) "sea surface temperature in the southeast has a warm bias [due in part to] erroneously weak equatorial winds," (4) "the warm bias evident along the coast of southern Africa is also partly a result of insufficient local upwelling," (5) "excess radiation is evident in the south stratocumulus region of up to 60 W/m^2," (6) there is "excess precipitation in the Southern Hemisphere," and (7) "errors in cloud parameterization lead to "massively excess solar radiation in austral winter and spring in CCSM4."

It is clear that many important aspects of clouds and cloud cover remain inadequately modeled. The cloud parameterization problem is extremely complex and will likely remain that way for the foreseeable future.

Writing in the *Journal of Geophysical Research (Atmospheres)*, Wang and Su (2013) note "coupled general circulation models (GCMs) are the major tool to predict future climate change, yet cloud-climate feedback constitutes the largest source of uncertainty in these modeled future climate projections." Thus they state "our confidence in the future climate change projections by the coupled GCMs to a large extent depends on how well these models simulate the observed present-day distribution of clouds and their associated radiative fluxes." About their own work, they write, "the annual mean climatology of top of the atmosphere (TOA) shortwave and longwave cloud radiative effects in 12 Atmospheric Model Intercomparison Project (AMIP)-type simulations participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) [was] evaluated and investigated using satellite-based observations, with a focus on the tropics."

The two researchers report the CMIP5 AMIPs "produce considerably less cloud amount [than what is observed], particularly in the middle and lower troposphere." Moreover, there are "good model simulations in tropical means," but they are "a result of compensating errors over different dynamical regimes." "Over the Maritime Continent," they note, "most of the models simulate moderately less high-cloud fraction, leading to weaker shortwave cooling and longwave warming and a larger net cooling," while "over subtropical strong subsidence regimes, most of the CMIP5 models strongly underestimate stratocumulus cloud amount and show considerably weaker local shortwave cloud radiative forcings," and "over the transitional trade cumulus regimes, a notable feature is that while at varying amplitudes, most of the CMIP5 models consistently simulate a deeper and drier boundary layer, more moist free troposphere, and more high clouds and consequently overestimate shortwave cooling and longwave warming effects there." They conclude, "representing clouds and their TOA radiative effects remains a challenge in the CMIP5 models."

In a revealing paper published in the American Meteorological Society's *Journal of Climate*, Lauer and Hamilton (2013) report numerous previous studies from the Coupled Model Intercomparison Project phase 3 (CMIP3) showed large biases in the simulated cloud climatology affecting all GCMs, as well as "a remarkable degree of variation among the models that represented the state of the art circa 2005." The two researchers set out to provide an update by describing the progress that has been made in recent years by comparing mean cloud properties, interannual variability, and the climatological seasonal cycle from the CMIP5 models with results from comparable CMIP3 experiments, as well as with actual satellite observations.

Lauer and Hamilton conclude "the simulated cloud climate feedbacks activated in global warming projections differ enormously among state-of-the-art models," while noting "this large degree of disagreement has been a constant feature documented for successive generations of GCMs from the time of the first Intergovernmental Panel on Climate Change assessment through the CMIP3 generation models used in the fourth IPCC assessment." They add, "even the model-simulated cloud climatologies for present-day conditions are known to depart significantly from observations and, once again, the variation among models is quite remarkable (e.g., Weare, 2004; Zhang *et al*., 2005; Waliser *et al*., 2007, 2009; Lauer *et al*., 2010; Chen *et al*., 2011)."

The two researchers determined (1) "long-term mean vertically integrated cloud fields have quite significant deficiencies in all the CMIP5 model simulations," (2) "both the CMIP5 and CMIP3 models display a clear bias in simulating too high LWP [liquid water path] in mid-latitudes," (3) "this bias is not reduced in the CMIP5 models," (4) there have been "little to no changes in the skill of reproducing the observed LWP and CA [cloud amount]," (5) "inter-model differences are still large in the CMIP5 simulations," and (6) "there is very little to no improvement apparent in the tropical and subtropical regions in CMIP5."

Lauer and Hamilton indicate there is "only very modest improvement in the simulated cloud climatology in CMIP5 compared with CMIP3," adding even this slightest of improvements "is mainly a result of careful model tuning rather than an accurate fundamental representation of cloud processes in the models."

It would therefore appear, given the findings described in this section, that the outlook for adequately modeling clouds and cloud processes must still be characterized as cloudy.

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1.3.5 Precipitation

1.3.5.1 Precipitation

Correctly simulating future precipitation has proven to be an extremely difficult task for modelers. One reason for the lack of success in this area is inadequate model resolution on both vertical and horizontal spatial scales, a limitation that forces climate modelers to parameterize the large-scale effects of processes (such as deep convection, which is the source of most precipitation) that occur on smaller scales than the models are capable of simulating. But there are other problems as well that result in vast differences between model projections and real-world observations. This section documents such problems and variances as they relate to model projections of precipitation.

In an early study of the subject, Lebel *et al.* (2000) compared rainfall simulations produced by a GCM with real-world observations from West Africa for the period 1960–1990. Their analysis revealed the model output was affected by a number of temporal and spatial biases that led to significant differences between observed and modeled data. The simulated rainfall totals, for example, were significantly greater than what was typically observed, exceeding real-world values by 25 percent during the dry season and 75 percent during the rainy season. In addition, the seasonal cycle of precipitation was not well simulated, as the researchers found the simulated rainy season began too early and the increase in precipitation was not rapid enough. Shortcomings were also evident in the GCM's inability to accurately simulate convective rainfall events, as it typically predicted too much precipitation. Furthermore, it was found "inter-annual variability [was] seriously disturbed in the GCM as compared to what it [was] in the observations." As for why the GCM performed so poorly in these several respects, Lebel *et al.* gave two main reasons: parameterization of rainfall processes in the GCM was much too simple, and spatial resolution was much too coarse.

Lau *et al.* (2006) considered the Sahel drought of the 1970s–1990s to provide "an ideal test bed for evaluating the capability of CGCMs [coupled general circulation models] in simulating long-term drought, and the veracity of the models' representation of coupled atmosphere-ocean-land processes and their interactions." They chose to "explore the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4," in which the 19 CGCMs "are driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions."

The climate scientists found "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, they report, "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events." All 19 of the CGCMs employed in the IPCC's *Fourth Assessment Report*, in other words, failed to adequately simulate the basic characteristics of "one of the most pronounced signals of climate change" of the past century—as defined by its start date, severity and duration."

Writing in *Science*, Wentz *et al.* (2007) noted the Coupled Model Intercomparison Project, as well as various climate modeling analyses, predicted an increase in precipitation on the order of 1 to 3 percent per °C of surface global warming. They decided to see what had happened in the real world in this regard over the prior 19 years (1987–2006) of supposedly unprecedented global warming, when data from the Global Historical Climatology Network and satellite measurements of the lower troposphere indicated there had been a global temperature rise on the order of 0.20°C per decade.

Using satellite observations obtained from the

Special Sensor Microwave Imager (SSM/I), the four Remote Sensing Systems scientists derived precipitation trends for the world's oceans over this period. Using data obtained from the Global Precipitation Climatology Project acquired from both satellite and rain gauge measurements, they derived precipitation trends for Earth's continents. Combining the results of these two endeavors, they derived a real-world increase in precipitation on the order of 7 percent per °C of surface global warming, somewhere between 2.3 and 7.0 times larger than what is predicted by state-of-the-art climate models.

How was this discrepancy to be resolved? Wentz *et al*. conclude the only way to bring the two results into harmony was for there to have been a 19-year decline in global wind speeds. But when looking at the past 19 years of SSM/I wind retrievals, they found just the opposite, an increase in global wind speeds. In quantitative terms, the two results were about as opposite as they could possibly be: "when averaged over the tropics from 30°S to 30°N, the winds increased by 0.04 m s^{-1} (0.6 percent) $decade^{-1}$, and over all oceans the increase was 0.08 m s^{-1} (1.0 percent) $decade^{-1}$," while global coupled ocean-atmosphere models or GCMs, in their words, "predict that the 1987-to-2006 warming should have been accompanied by a decrease in winds on the order of 0.8 percent $decade^{-1}$."

Wentz *et al*. state, "the reason for the discrepancy between the observational data and the GCMs is not clear." They also observe this dramatic difference between the real world of nature and the virtual world of climate modeling "has enormous impact" and the questions raised by the discrepancy "are far from being settled."

In a separate paper published that year, Allan and Soden (2007) quantified trends in precipitation within ascending and descending branches of the planet's tropical circulation and compared their results with simulations of the present day and projections of future changes provided by up to 16 state-of-the-art climate models. The precipitation data for this analysis came from the Global Precipitation Climatology Project (GPCP) of Adler *et al.* (2003) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) data of Xie and Arkin (1998) for the period 1979–2006, while for the period 1987–2006 the data came from the monthly mean intercalibrated Version 6 Special Sensor Microwave Imager (SSM/I) precipitation data described by Wentz *et al.* (2007).

The researchers report "an emerging signal of rising precipitation trends in the ascending regions and decreasing trends in the descending regions are detected in the observational datasets," but "these trends are substantially larger in magnitude than present-day simulations and projections into the 21st century," especially in the case of the descending regions. More specifically, for the tropics "the GPCP trend is about 2–3 times larger than the model ensemble mean trend, consistent with previous findings (Wentz *et al*., 2007) and also supported by the analysis of Yu and Weller (2007)," who additionally contended "observed increases of evaporation over the ocean are substantially greater than those simulated by climate models." In addition, Allan and Soden note "observed precipitation changes over land also appear larger than model simulations over the 20th century (Zhang *et al*., 2007)."

Noting the difference between the models and real-world measurements "has important implications for future predictions of climate change," Allan and Soden state "the discrepancy cannot be explained by changes in the reanalysis fields used to subsample the observations but instead must relate to errors in the satellite data or in the model parameterizations." This dilemma also was faced by Wentz *et al*. (2007), and they too state the resolution of the issue "has enormous impact" and likewise conclude the questions raised by the discrepancy "are far from being settled."

According to Lin (2007), "a good simulation of tropical mean climate by the climate models is a prerequisite for their good simulations/predictions of tropical variabilities and global teleconnections," but "unfortunately, the tropical mean climate has not been well simulated by the coupled general circulation models (CGCMs) used for climate predictions and projections." They note "most of the CGCMs produce a double-intertropical convergence zone (ITCZ) pattern" and they acknowledge "a synthetic view of the double-ITCZ problem is still elusive."

Lin analyzed tropical mean climate simulations of the 20-year period 1979–1999 provided by 22 IPCC *Fourth Assessment Report* CGCMs, together with concurrent Atmospheric Model Intercomparison Project (AMIP) runs from 12 of them. This revealed, in Lin's words, that "most of the current state-of-the-art CGCMs have some degree of the double-ITCZ problem, which is characterized by excessive precipitation over much of the Tropics (e.g., Northern Hemisphere ITCZ, Southern Hemisphere SPCZ [South Pacific Convergence Zone], Maritime Continent, and equatorial Indian Ocean), and often associated with insufficient precipitation over the equatorial Pacific," as well as "overly strong trade winds, excessive LHF [latent heat flux], and insufficient SWF [shortwave flux], leading to significant cold SST (sea surface temperature) bias in much of the tropical oceans."

Lin further notes "most of the models also simulate insufficient latitudinal asymmetry in precipitation and SST over the eastern Pacific and Atlantic Oceans," and "the AMIP runs also produce excessive precipitation over much of the Tropics including the equatorial Pacific, which also leads to overly strong trade winds, excessive LHF, and insufficient SWF." All of this suggests "the excessive tropical precipitation is an intrinsic error of the atmospheric models," Lin writes, adding, "over the eastern Pacific stratus region, most of the models produce insufficient stratus-SST feedback associated with insufficient sensitivity of stratus cloud amount to SST."

With the solutions to all of these longstanding problems continuing to remain "elusive," and with Lin suggesting the sought-for solutions are in fact prerequisites for "good simulations/predictions" of future climate, there is significant reason to conclude that current state-of-the-art CGCM predictions of CO_2-induced global warming should not be considered reliable.

Lavers *et al.* (2009) examined the predictive skill of eight seasonal climate forecast models developed at various European climate centers. Specifically, they assessed the predictability of monthly precipitation "retrospective forecasts" or hindcasts, composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001. They compared the projections against real-world precipitation values obtained from Global Precipitation Climatology Center data. In addition, they conducted a virtual-world analysis, where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

These analyses indicate that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but there was a large drop off in predictive skill in the second 15-day period. Things were even worse in the real world, where the models had negligible skill over land at a 31-day lead time, which the researchers describe as being "a relatively short lead time in terms of seasonal climate prediction." The three researchers conclude that given the lack of real-world skill demonstrated by models, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they frankly state "may prove to be elusive."

Anagnostopoulos *et al.* (2010) compared observed versus modeled precipitation values over the twentieth century for 55 locations across the globe. Their results indicate the six models investigated (three from the IPCC's *Third Assessment* and three from its *Fourth Assessment*) reproduced only poorly the observed precipitation values over the period of study. In far too many instances the models showed a rise in precipitation when observed values actually fell, or vice versa. The models fared worse when a similar analysis was conducted in the aggregate for the entire conterminous United States. Model output differed "substantially" from the observed time series, with annual precipitation values overestimating observed values by up to 300 mm, or 40 percent. The authors also state the results from the three models used in the IPCC's *Fourth Assessment Report* were "no better" than the three models used in the IPCC's *Third Assessment Report*.

Ault *et al*. (2012) write "the last generation of models, those comprising [the] Climate Model Intercomparison Project III (CMIP3) archive, was unable to capture key statistics characterizing decadal to multidecadal (D2M) precipitation fluctuations," noting specifically "CMIP3 simulations overestimated the magnitude of high frequency fluctuations and consequently underestimated the risk of future decadal-scale droughts." Since "a new generation of coupled general circulation models (GCMs) has been developed and made publicly available as part of the Climate Model Intercomparison Project 5 (CMIP5) effort," it is critical, the note, "to evaluate the ability of these models to simulate realistic 20th century variability regionally and across a variety of timescales."

Using gridded (2.5 x 2.5) version 4 reanalysis product data made available to them by the Global Precipitation Climatology Centre (Rudolf *et al*., 2005)—which spanned the period January 1901 through December 2007—Ault *et al*. assessed the magnitude of D2M variability in new CMIP5 simulations. The three U.S. researchers report their results suggest "CMIP5 simulations of the historical era (1850–2005) underestimate the importance [of] D2M variability in several regions where such behavior is prominent and linked to drought," namely, "northern Africa (e.g., Giannini *et al*., 2008), Australia (Cai *et al*., 2009; Leblanc *et al*., 2012), western North America (Seager, 2007; Overpeck and Udall, 2010), and the Amazon (Marengo *et al*., 2011)."

Ault *et al*. further state "the mismatch between 20th century observations and simulations suggests that model projections of the future may not fully represent all sources of D2M variations," noting, "if observed estimates of decadal variance are accurate, then the current generation of models depict D2M precipitation fluctuations that are too weak, implying that model hindcasts and predictions may be unable to capture the full magnitude of realizable D2M fluctuations in hydroclimate." As a result, "the risk of prolonged droughts and pluvials in the future may be greater than portrayed by these models."

Aaliser *et al*. (2011) write, "key to the proper use of satellite retrievals in the evaluation of modeled cloud ice and liquid is that many global climate model representations ignore or diagnostically treat the falling hydrometeor components (e.g., rain and snow) and only consider—for the purposes of radiation calculations—the 'suspended' component of water that the model deems 'clouds.'" They state "the variations in the annual mean integrated ice water path and liquid water path between global climate models contributing to the IPCC AR4 range over two orders of magnitude," citing Li *et al*. (2008) and Waliser *et al*. (2009). Employing estimates of cloud and precipitating ice mass and characterizations of its vertical structure supplied by CloudSat retrievals, Waliser *et al*. set out to perform radiative transfer calculations "to examine the impact of excluding precipitating ice on atmospheric radiative fluxes and heating rates."

According to the four researchers, the exclusion of precipitating ice "can result in underestimates of the reflective shortwave flux at the top of the atmosphere (TOA) and overestimates of the down-welling surface shortwave and emitted TOA longwave flux, with the differences being about 5–10 Wm^{-2} in the most convective and rainfall intensive areas." In addition, they report, "there are also considerable differences (~10-25%) in the vertical profiles of shortwave and longwave heating, resulting in an overestimation (~up to 10%) of the integrated column cooling." And they state "the magnitude of these potential errors is on the order of the radiative heating changes associated with a doubling of atmospheric carbon dioxide."

With respect to the implications of their findings, Waliser *et al*. state "when the above results are considered in the context of a climate model simulation, the changes would not only impact the radiative heating of the atmosphere but would be expected to impact the circulation, and possibly even the manner the model adjusts to external forcings such as increasing greenhouse gases." In addition, they note, since the "models are tuned to get the right TOA radiation balance, the implications here are that without considering the ice in precipitating hydrometeors explicitly, the models will be getting the right result (i.e., TOA balance) for the wrong reasons," and "in doing so, there are likely to be compensating errors in other quantities such as cloud cover, cloud particle effective radius and/or cloud mass."

In another paper, Soncini and Bocchiola (2011) note "General Circulation Models (GCMs) are widely adopted tools to achieve future climate projections." However, they write, "one needs to assess their accuracy, which is only possible by comparison of GCMs' control runs against past observed data," which they proceeded to do in the case of snowfall regimes within the Italian Alps. Specifically, the two Italian researchers investigated the accuracy of simulations of snowfall throughout the Italian Alps provided by two GCMs (HadCM3, CCSM3), which are included within the family of models employed by the IPCC. This was done by comparing the models' output with a set of comprehensive ground data obtained from some 400 snow-gauging stations located within the region of interest for the period 1990–2009.

In examining the model versus observation comparison, Soncini and Bocchiola determined "the investigated GCMs provide poor depiction of the snowfall timing and amount upon the Italian Alps," noting, in fact, the HadCM3 model actually "displays considerable snowfall during summer," which they indicate "is clearly not supported by ground data." In addition, they report obtaining "contrasting results between the two models," with HadCM3 providing substantially constant volumes of snow received over time and CCSM3 projecting decreasing snowfall volumes. "Overall," in the words of the two researchers, "given the poor depiction of snowfall by the GCMs here tested, we suggest that care should be taken when using their outputs for predictive purposes."

Also investigating snowfall were Salzmann and Mearns (2012), who note "climate impact assessments require primarily regional- to local-scale climate data for the past and the present and scenarios for the future," stating, with respect to the future, that "regional climate models (RCMs) are among the most promising tools to simulate climate on the regional scale." However, they also note "the effective benefit of each of these RCMs and their ensembles for specific climate impact assessments remains to be proven for individual impact studies." Salzmann and Mearns explore this issue within the context of the North American Regional Climate Change Program (NARCCAP; Mearns *et al*., 2009) with regard to the seasonal snow regime in the Upper Colorado River Basin. They compared NARCCAP results with *in situ* observations and data obtained from various reanalysis projects.

The two researchers at the National Center for Atmospheric Research in Boulder, Colorado (USA) report—quite bluntly and to the point: "[T]he RCMs are generally too dry, too warm, simulate too little snow water equivalent, and have a too-short snow cover duration with a too-late start and a too-early end of a significant snow cover." To these problems they add, "attributing the found biases to specific features of the RCMs remains difficult or even impossible without detailed knowledge of the physical and technical specification of the models."

Stewart *et al*. (2011) write, "regional climate models project that future climate warming in Central Europe will bring more intense summer-autumn heavy precipitation and floods as the atmospheric concentration of water vapor increases and cyclones intensify," citing the studies of Arnell and Liu (2001), Christensen and Christensen (2003), and Kundzewicz *et al*. (2005). In an exercise designed to assess the reasonableness of these projections, Stewart *et al*. derived "a complete record of paleofloods, regional glacier length changes (and associated climate phases) and regional glacier advances and retreats (and associated climate transitions) … from the varved sediments of Lake Silvaplana (ca. 1450 BC–AD 420; Upper Engadine, Switzerland)," while indicating "these records provide insight into the behavior of floods (i.e. frequency) under a wide range of climate conditions."

The five researchers report uncovering pertinent data from the period they investigated that suggests "an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June-July-August temperatures," which further suggests—as they also note—the frequency of flooding "was reduced during warm and/or dry climates." In reiterating that "the findings of this study suggest that the frequency of extreme summer-autumn precipitation events (i.e. flood events) and the associated atmospheric pattern in the Eastern Swiss Alps was not enhanced during warmer (or drier) periods," Stewart *et al*. acknowledge "evidence could not be found that summer-autumn floods would increase in the Eastern Swiss Alps in a warmer climate of the 21st century," pretty much debunking the projections of regional climate models that have suggested otherwise.

Soares *et al*. (2012) note "Regional Climate Models (RCMs) are increasingly used to assess the impact of climate change at regional and local scales (Giorgi and Mearns, 1999; Wang *et al*., 2004; Christensen and Christensen, 2007)," because "in regions where local features affecting the atmospheric flow, such as topography and coastal processes, are prevalent, finer resolution simulations with state-of-the-art mesoscale models are required to reproduce observed weather and climate (Mass *et al*., 2002; Salathe *et al*., 2008)." They utilized "a new data set of daily gridded observations of precipitation, computed from over 400 stations in Portugal, to assess the performance of 12 regional climate models at 25-km resolution, from the ENSEMBLES set, all forced by ERA-40 boundary conditions, for the 1961–2000 period," while "standard point error statistics, calculated from grid point and basin aggregated data, and precipitation related climate indices are used to analyze the performance of the different models in representing the main spatial and temporal features of the regional climate, and its extreme events."

Although the five Portuguese researchers say the models achieved what they called a "good representation" of the features listed above, they also list a number of less-than-hoped-for results: (1) "10 of the 12 analyzed models under-predict Portuguese precipitation," (2) "half of the models under-represent observed variability of daily precipitation," (3) "models were found to underestimate the number of wet days," (4) "grid point percentiles of precipitation are generally under-predicted," (5) "in all cases, there is a significant model spread," (6) "the 95th percentile is under-predicted by all models in most of the country," and (7) "there is an important model spread in all analyzed variables." Such findings led Soares *et al*. to state in their concluding paragraph, "the present results suggest that there is still some way to go in this research."

Focusing on a nearby region, Kelley *et al*. (2012) state "winter and summer Mediterranean precipitation climatology and trends since 1950 as simulated by the newest generation of global climate models, the Coupled Model Intercomparison Project phase 5 (CMIP5), [were] evaluated with respect to observations and the previous generation of models (CMIP3) used in the Intergovernmental Panel on Climate Change Fourth Assessment Report," with the objective of determining "to what extent we can trust the multi-model mean (MMM) trends as representing the externally forced trends." Upon analysis, Kelly *et al*. determined "the Mediterranean precipitation trends of the last half century in the CMIP5 MMMs and the observations differ significantly, particularly in winter and over the northern Mediterranean region." The CMIP5 MMM trend, for example, "indicates a modest drying throughout the seasonal cycle, with the strongest drying in the March, April and May spring season." The observed trend, on the other hand, "shows a predominantly winter drying," and they state "it is not entirely clear what causes this discrepancy."

Although the four researchers report "there is a modest improvement of the CMIP5 climatology over CMIP3," it would appear "modest" is too generous a word to describe what was accomplished between the development of the CMIP3 and CMIP5 models, particularly given their conclusion that the slight improvement they detected may have been due merely to the "improved horizontal resolution" of the CMIP5 models. The ultimate implication of Kelly *et al*.'s findings is presented in the concluding paragraph of their paper, where they state their findings "reinforce the need for further research and better understanding of the mechanisms driving the region's hydroclimate."

Also working in the Mediterranean region, Barkhordarian *et al*. (2013) assessed the role of anthropogenic forcing due to greenhouse gases and sulphate aerosols (GS) in recently observed precipitation trends over the Mediterranean region in order to determine whether the observed trends over the period 1966–2005 (over land) and 1979–2008 (over land and sea) "are consistent with what 22 models project as response of precipitation to GS forcing," where "significance is estimated using 9,000-year control runs derived from the CMIP3 archive."

The three researchers discovered "the observed trends are markedly inconsistent with expected changes due to GS forcing," as "observed changes are several times larger than the projected response to GS forcing in the models." But they state "the most striking inconsistency" was "the contradiction between projected drying and the observed increase in precipitation in late summer and autumn." Coming to a conclusion that cannot be avoided, Barkhordarian *et al*. therefore state "the detection of an outright sign mismatch of observed and projected trends in autumn and late summer, leads us to conclude that the recently observed trends cannot be used as an illustration of plausible future expected change in the Mediterranean region," once again illustrating the many problems besetting even the best of climate models.

In another paper, Miao *et al*. (2012) assessed the performance of the AR4 GCMs (CMIP3 models) in simulating precipitation and temperature in China from 1960 to 1999 by comparing the model simulations with observed data, using "system bias (*B*), root-mean-square error (*RMSE*), Pearson correlation coefficient (*R*) and Nash-Sutcliffe model efficiency (*E*)" as evaluation metrics. The four researchers conclude certain of the CMIP3 models "are unsuitable for application to China, with little capacity to simulate the spatial variations in climate across the country," adding all of them "give unsatisfactory simulations of the inter-annual temporal variability." In addition, they found "each AR4 GCM performs differently in different regions of China." In light of these findings, Miao *et al*. conclude "the inter-annual simulations (temperature and precipitation) by AR4 GCMs are not suitable for direct application," and "caution should be applied when using outputs from the AR4 GCMs in hydrological and ecological assessments" because of their "poor performance."

Kataoka *et al*. (2012) note the Indian Ocean Subtropical Dipole (IOSD; Behera *et al*., 2000; Behera and Yamagata, 2001) is "one of the climate modes that generate climate variations in the Southern Hemisphere," having "a great impact on the surrounding countries through its influence on the rainfall (Behera and Yamagata, 2001; Reason, 2001; Washington and Preston, 2006)." This mode is characterized by "a dipole pattern in the sea surface temperature anomaly in the southern Indian Ocean with a warm (cold) southwestern pole and cold (warm) northeastern pole during austral summer." "[S]ince southern Africa is one of the most vulnerable regions to abnormal weather events," they note, "an accurate prediction of the IOSD together with its influence on rainfall is necessary to mitigate the impacts." Using observational data and mathematical outputs from 22 coupled general circulation models (CGCMs) submitted to the World Climate Research

Programme's Coupled Model Intercomparison Project phase 3 (CMIP3), Kataoka *et al*. proceeded to assess each model's ability to simulate the IOSD and its influence on rainfall anomalies over southern Africa.

In discussing their findings, the four Japanese researchers report the location and orientation of sea surface temperature anomaly poles "differ considerably" from one model to another, owing primarily to model biases in sea level pressure anomalies. This finding, as they describe it, supports "the earlier results of Morioka *et al*. (2010) based on an ocean general circulation model." This problem, in their words, "may partly explain the poor skills of CGCMs in simulating the influence of the IOSD on the rainfall anomalies." In addition, they state "some models fail to simulate the statistical relation between the positive (negative) rainfall anomaly and La Niña (El Niño)." The authors conclude "more accurate simulation of the IOSD as well as the influence of the ENSO is necessary to improve the seasonal prediction of southern African rainfall."

According to Jiang *et al*. (2013), "multi-scale temporal variability of precipitation has an established relationship with floods and droughts," and GCMs can provide "important avenues to climate change impact assessment and adaptation planning," but only if they possess an "ability to capture the climatic variability at appropriate scales." Jiang *et al*. assessed "the ability of 16 GCMs from the Bias Corrected and Downscaled (BCSD) World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) projections and 10 Regional Climate Models (RCMs) that participated in the North American Regional Climate Change Assessment Program (NARCCAP) to represent multi-scale temporal variability determined from observed station data." They focused on four regions in the Southwest United States—Los Angeles, Las Vegas, Tucson, and Cimarron—because these places "represent four different precipitation regions classified by clustering method." They specifically investigated "how storm properties and seasonal, inter-annual, and decadal precipitation variabilities differed between GCMs/RCMs and observed records in these regions."

The four U.S. researchers report "RCMs tend to simulate [1] longer duration, [2] shorter inter-storm periods, and [3] lower storm intensity than observed." Moreover, they state [4] "RCMs fail to simulate high average storm intensity during the summer period as seen in observed precipitation records." They also say [5] bias-corrected and downscaled GCMs "lack the ability to reproduce observed monthly precipitation patterns." In addition, they note "observed precipitation tends to be above average during the PDO warm phase, while precipitation during the PDO cold phase is below average," and [6] "most of the considered GCMs failed to reproduce similar variability." Their wavelet analysis revealed [7] "even the successful GCMs on reproducing the low-frequency variability associated with ENSO and PDO, showed inconsistency in the occurrence or timing of 2–8-year bands." Jiang *et al*. conclude their "comparative analyses suggest that current GCMs/RCMs do not adequately capture multi-scale temporal variability of precipitation," and, therefore, "using GCM/RCM output to conduct future flood projections is not creditable."

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1.4.5.2 Monsoons

Climate modelers have long struggled to simulate seasonal monsoons despite their significance in global climate. As mentioned in a prior section of this chapter, when the 2004 summer monsoon season of India experienced a 13 percent deficit not predicted by either empirical or dynamical models used in making rainfall forecasts, Gadgil *et al*. (2005) decided to perform a historical analysis of the models' skills over the period 1932 to 2004. They found despite numerous model changes and an ever-improving understanding of monsoon variability, Indian monsoon model forecasting skill had not improved since 1932. Large differences often were observed when comparing monsoon rainfall measurements with empirical model predictions; and the models often failed to correctly predict even the *sign* of the precipitation anomaly.

Dynamical models fared even worse. In comparing observed versus predicted monsoon rainfall from 20 atmospheric general circulation models and one supposedly superior coupled atmosphere-ocean model, Gadgil *et al*. report none was able "to simulate correctly the interannual variation of the summer monsoon rainfall over the Indian region." Like the empirical models, they frequently failed to simulate not only the magnitude but also the sign of the real-world rainfall anomalies. Few improvements seem to have occurred since that time.

Zhang *et al*. (2012) report "the Asian monsoon is a major component in the global climate system, characterized by remarkable seasonal and inter-annual rainfall variations which have significant social and economic influences on large populations in the region," the complexity of which, in their words, "is never overstated." Using daily precipitable water and 850 hPa monsoon wind data, which in the words of Zhang *et al*. "represent large-scale moisture and dynamic conditions for monsoon development," the four scientists analyzed "potential changes in Asian monsoon onset, retreat and duration simulated by 13 IPCC AR4 models."

The Chinese-Australian research team report there "is no single outstanding model out of the 13 models used in the analysis," noting "some of the models have shown significant biases in mean onset/retreat dates and some failed to produce the broad features of how [the] monsoon evolves." Over East Asian land, for example, they found "the models are nearly equally divided about the sign of potential changes of onset/retreat." And, sounding rather frustrated, they lament they "do not know why the models are different in simulating these dominant processes and why in some models the ENSO influence is more significant than others," adding "it is unclear what are the key parameterizations leading to the differences in simulating ENSO and its responses to global warming," citing Solomon *et al.* (2007) and Wang *et al.* (2009). They conclude, "there is a long way ahead before we can make skillful and reliable prediction of monsoon onset, duration, intensity and evolution in [a] warmed climate."

In another study, Kim *et al.* (2012) note "the Asian monsoon influences almost half of the world's population with their agriculture, life and society depending on monsoon climate" and, therefore, "understanding the physical processes that determine the character of the monsoon systems and also providing accurate extended range predictions on a seasonal timescale is crucial for the economy and policy planning in the monsoon regions."

Kim *et al.* assessed the seasonal prediction skill regarding the Asian summer monsoon via the use of "retrospective predictions (1982–2009) from the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) seasonal prediction systems." The four researchers state, "in both SYS4 and CFSv2, a cold bias of sea-surface temperature (SST) is found over the Equatorial Pacific, North Atlantic [and] Indian Oceans," as well as "over a broad region in the Southern Hemisphere relative to observations," and "a warm bias is found over the northern part of the North Pacific and North Atlantic." In addition, they state "excessive precipitation is found along the Intertropical Convergence Zone, equatorial Atlantic, equatorial Indian Ocean and the maritime continent." And they find "the southwest monsoon flow and the Somali Jet are stronger in SYS4, while the south-easterly trade winds over the tropical Indian Ocean, the Somali Jet and the Subtropical northwestern Pacific high are weaker in CFSv2 relative to the reanalysis." With both of the world's most advanced climate modeling systems "performing poorly," in the estimation of Kim *et al.*, in simulating monsoon precipitation that affects almost half of the world's population, it would appear the climate modeling enterprise has a long way to go before confidence can be placed in its projections, whether under CO_2 forcing or otherwise.

Wu and Zhou (2013) sought to evaluate the performance of the Flexible Global Ocean-Atmosphere-Land System model, Spectral Version 2 (FGOALS-s2)—a CGCM developed by the National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics of the Chinese Academy of Sciences—with respect to its ability to simulate the relationship between ENSO and the East Asian-western North Pacific (EA-WNP) monsoon. The two authors write, "after nearly five years of effort," the original model (Wu *et al.*, 2009) "has been improved in various facets" and it was therefore necessary "to carefully assess the ENSO-monsoon relationship in the current version of the model."

Wu and Zhou noted several problems with the model: it "fails to simulate the asymmetry of the wintertime circulation anomalies over the WNP between El Niño and La Niña"; "the simulated anomalous cyclone over the WNP (WNPAC) associated with La Niña is generally symmetric about the WNPAC associated with El Niño, rather than shifted westward as that in the observation"; "simulated La Niña events decay much faster than observed," and "the precipitation anomalies over East Asia, especially those of the Meiyu rain belt, are much weaker than that in the observation."

According to Chaudhari *et al.* (2013), "despite the potential for tropical climate predictability, and the advances made in the development of climate models, the seasonal dynamical forecast of [the] Indian summer monsoon remains a challenging problem," which explored via a study of model biases and how they create further biases as they wend their way through multiple stages of both simultaneous and sequential processes. Chaudhari *et al.* examined the performance of the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) over the Indian monsoon region in a 100-year-long coupled run, framed "in terms of biases of sea surface temperature (SST), rainfall and circulation," while also exploring "the role of feedback processes in maintaining these biases."

According to the nine researchers, the model shows dry (wet) rainfall bias concomitant with cold (warm) SST bias over the east (west) equatorial Indian Ocean. They say these biases of SST and rainfall affect both lower- and upper-level circulations in a feedback process, which in turn regulates the SST and rainfall biases by maintaining a coupled feedback process. Subsequently, a dry (wet) rainfall bias over the east (west) Indian Ocean induces anomalous low level easterlies over the tropical Indian Ocean and causes cold SST bias over the east Indian Ocean by triggering evaporation and warm SST bias over the west Indian Ocean through advection of warm waters. They find the persistent SST bias then retains the zonal asymmetric heating and meridional temperature gradient, resulting in a circum-global subtropical westerly jet core, which in turn magnifies the mid-latitude disturbances and decreases the Mascarene high, which in its turn diminishes the strength of monsoon cross-equatorial flow and results in less upwelling as compared to that in the observations. The latter phenomenon, they say, increases the SST bias over the West Indian Ocean. In conclusion, Chaudhari *et al*. state, "the coupled interaction among SST, rainfall and circulation works in tandem through a closed feedback loop to maintain the model biases over the tropical Indian Ocean."

In one additional study on the Asian monsoon, Bollasina and Ming (2013) note most current general circulation models "show a remarkable positive precipitation bias over the southwestern equatorial Indian Ocean (SWEIO), which can be thought of as a westward expansion of the simulated IO convergence zone toward the coast of Africa." They further note "the bias is common to both coupled and uncoupled models, suggesting that its origin does not stem from the way boundary conditions are specified."

To further explore this issue, Bollasina and Ming "comprehensively characterized" "the spatio-temporal evolution of the precipitation and associated three-dimensional atmospheric circulation biases … by comparing the GFDL [Geophysical Fluid Dynamics Laboratory] AM3 atmospheric model to observations."

In the words of the two researchers, "the oceanic bias, which develops in spring and reduces during the monsoon season, is associated [with] a consistent precipitation and circulation anomalous pattern over the whole Indian region," where "in the vertical, the areas are linked by an anomalous Hadley-type meridional circulation, whose northern branch subsides over northeastern India significantly affecting the monsoon evolution (e.g., delaying its onset)." They find "the ability of local anomalies over the SWEIO to force a large-scale remote response to the north is further supported by numerical experiments with the GFDL spectral dry dynamical core model."

Bollasina and Ming say their study "makes the case that the precipitation bias over the SWEIO is forced by the model excess response to the local meridional sea surface temperature gradient through enhanced near-surface meridional wind convergence." They thus conclude "a detailed investigation into the model physics to identify possible parameters which may alleviate the model bias would be the natural extension of this work."

Shifting to the African monsoon, writing as background for their work, authors Zheng and Braconnot (2013) report "despite recent progress in the monitoring and understanding of the WAM [West African Monsoon] within the framework of the African Monsoon Multidisciplinary Analysis (AMMA), there are still large uncertainties in projections of future climate in this region, such that even the sign of future precipitation change is uncertain," citing Solomon *et al*. (2007). The authors "revisit the results of PMIP2 simulations over Africa using two approaches." The first "considers the ensemble of simulations in order to determine how well the PMIP2 models [of today] reproduce some of the basic features of the summer monsoon precipitation," while the objective of the second is "to understand model differences by considering model characteristics for present-day climate and their sensitivities to insolation change."

The scientists learned several things from the simulations. First, they report, the "meridional temperature gradient is underestimated between 0° and 20°N by the PMIP2 model median, resulting in a smaller gradient of sea level pressure between the Gulf of Guinea and [the] Sahel," which helps to explain "a lower than observed low-level moisture flux and an underestimate of rainfall intensity when compared with observations." Second, "the northward extent of the rain belt and the intensity of precipitation change are underestimated." Third, "the models overestimate the solar radiation." Fourth, the models "underestimate the cloud radiative forcing in deep and moderate convective regimes." And fifth, "some of the models have too strong a coupling between the latent heat and convection in deep convective regimes."

Moving across the Atlantic to North America, according to Cerezo-Mota *et al*. (2011), "the North American monsoon (NAM) is the regional-scale atmospheric circulation system (Stensrud *et al*., 1997) responsible for the dramatic increase in precipitation during the summer in northwestern Mexico and the southwest United States (Grantz *et al*., 2007)." They state "understanding the mechanisms that govern the timing and intensity, as well as the impacts of climate change on the NAM, is a priority for the scientific community, watershed managers and farmers in the NAM area" because "the impacts of droughts/floods are devastating."

Cerezo-Mota *et al*. investigated the degree of realism in its simulation by a major regional climate model (RCM)—the Hadley Centre Regional Model version 3P (HadRM3P)—analyzing the moisture sources of the NAM by employing two different boundary-condition data sets used to drive the model, which allowed them to assess the ability of the RCM to reproduce rainfall under climate-change conditions in the NAM region as predicted by GCMs.

As a result of their tests, the three U.K. researchers determined "two of the most commonly used GCMs that simulate well the NAM precipitation (HadCM3 and MIROC) do not reproduce correctly the Great Plains low-level jet nor the moisture in the Gulf of Mexico," both of which play major roles in the northern portion of the NAM. The implication of their results, in the words of Cerezo-Mota *et al*., is that "precipitation in Arizona-New Mexico would not be correctly represented by a regional model driven by these GCMs." Thus, they write RCMs driven by the "most commonly used" GCMs "would not give realistic simulations of the current climate of the region and therefore would not offer a realistic projection of climate change of the NAM."

Moving further south and using real-world data pertaining to the onset, end, and total rainfall of the South American Monsoon System (SAMS)—as characterized by precipitation data for the period 1979–2006, derived from the Global Precipitation Climatology Project—Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models with distinct physics and resolutions to simulate real-world SAMS characteristics. Over northern South America, they find the annual precipitation cycle "is poorly represented by most models" and "most models tend to underestimate precipitation during the peak of the rainy season." In addition, they write, "the misrepresentation of the Intertropical Convergence Zone and its seasonal cycle seems to be one of the main reasons for the unrealistic out-of-phase annual cycles simulated near the equator by many GCMs" and "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." As a consequence, they note, "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon for most models."

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1.4.5.3 Extreme Precipitation

Atmospheric general circulation models (GCMs) predict the planet's hydrologic cycle will intensify as the world warms, leading to an increase in the frequency and intensity of extreme precipitation events. In an early review of the subject, Walsh and Pittock (1998) reported "there is some evidence from climate model studies that, in a warmer climate, rainfall events will be more intense" and "there is considerable evidence that the frequency of extreme rainfall events may increase in the tropics." Upon further study, however, they concluded, "because of the insufficient resolution of climate models and their generally crude representation of sub-grid scale and convective processes, little confidence can be placed in any definite predictions of such effects."

More than a decade later, Lim and Roderick (2009) compared the water cycle characteristics of the 39 model runs used in the IPCC AR4 (2007) assessment. The range of annual average global precipitation for the period 1970–1999 was 916.5 to 1,187.2 mm/yr. For the A1B scenario of CO_2 increase over the twenty-first century the increase in model precipitation ranged between 22.9 and 69.1 mm/yr with those that warmed the most generally showing greater increase in precipitation. The rate of increase in precipitation with temperature over the period, averaged about 2%/°C. A surprising result was the marked difference in the distribution of rainfall increase: At one extreme most rainfall was over the land, and at the other it was mostly over the oceans; the other models fell across the range between the extremes.

A detailed analysis of how the models compared over Australia demonstrated even more variability. Lim and Roderick found the 1970–1999 annual rainfall of the models ranged from 190.6 mm to 1059.1 mm, whereas the observed rainfall is in the range between 400 and 500 mm. Across the twenty-first century under the A1B scenario, 24 models returned an increase in precipitation over Australia, while 15 showed decreases. Some models had the evaporation over Australia (and the Middle East) exceeding precipitation.

Stephens *et al.* (2010) write that in prior studies "land surface observations of the daily-accumulated rainfall intensities of rates >1 mm/day were compiled from the Global Historical Climatology Network by Sun *et al*. (2006) and compared to analogous model accumulated precipitation," and they report "as in other studies (e.g., Dai and Trenberth, 2004), the Sun *et al*. comparison revealed a general overestimate in the frequency of modeled precipitation and an associated underestimate of intensity," while noting "Wilcox and Donner (2007) reached a similar conclusion." To further examine the issue Stephens *et al*. focused on the much larger portion of the planet that is occupied by oceans, using "new and definitive measures of precipitation frequency provided by CloudSat [e.g., Haynes *et al.,* 2009]" to assess the realism of global model precipitation. Their analysis employed five different computational techniques representing "state-of-the-art weather prediction models, state-of-the-art climate models, and the emerging high-resolution global cloud 'resolving' models."

Stephens *et al*. determined "the character of liquid precipitation (defined as a combination of accumulation, frequency, and intensity) over the global oceans is significantly different from the character of liquid precipitation produced by global weather and climate models," noting "the differences between observed and modeled precipitation are larger than can be explained by observational retrieval errors or by the inherent sampling differences between observations and models." More specifically, they report for the oceans as a whole, "the mean model intensity lies between 1.3 and 1.9 times less than the averaged observations" and occurrences "are approximately twice the frequency of observations." They also note the models "produce too much precipitation over the tropical oceans" and "too little mid-latitude precipitation." And they indicate the large model errors "are not merely a consequence of inadequate upscaling of observations but indicative of a systemic problem of models more generally."

In concluding their study, the nine U.S., U.K., and Australian researchers say their results imply state-of-the-art weather and climate models have "little skill in precipitation calculated at individual grid points" and "applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

In a study published in the *Journal of Climate*, Rossow *et al*. (2013) write "some of the concern about possible negative impacts of a warming climate is focused on possible increases of precipitation extremes." They sought to "exploit more than a decade of independent cloud and precipitation data products covering the whole tropics (15°S-15°N) to more clearly separate the contributions to average precipitation intensity and daily average accumulation rate made by the different types of deep convective systems," focusing on the period 1998–2008.

The four researchers determined "the whole distribution of instantaneous precipitation intensity and daily average accumulation rate is composed of (at least) two separate distributions representing distinctly different types of deep convection associated with different meteorological conditions." In particular, they found the extreme portion of the tropical precipitation intensity distribution "is produced by 40% of the larger, longer-lived mesoscale-organized type of convection with only about 10% of the ordinary convection occurrences producing such intensities." When accumulation rates were considered, they found "essentially all of the values above 2 mm/hour are produced by the mesoscale systems."

Rossow *et al*. note "all of the climate GCMs currently parameterize tropical deep convection as a single process, localized to individual grid cells (on the order of 25-200 km in size) with short lifetimes (on the order of minutes to a few hours) that most resembles ordinary cumulonimbus." Thus, "today's atmospheric models do not represent mesoscale-organized deep convective systems that are generally larger than current-day circulation model grid cell sizes but smaller than the resolved dynamical scales."

On the basis of these observations, the four researchers contend "the observed distinctive behavior of the different deep convective storm types undercuts the simple projection of changes of extremes based on the large-scale balances or by a simple scaling." And they say "these results draw attention to the need to understand why different deep convective storm types exist, how they interact with each other and with the larger-scale circulation, and what role they each play in the atmospheric general circulation." With respect to the ultimate consequence of these model deficiencies, in the concluding sentence of their paper the four researchers state: "Until the full range of deep convective processes in the tropics is more realistically represented in climate models, they cannot be used to predict the changes of extreme precipitation events in a changing (warming) climate."

Schleip *et al.* (2010) compared the results of six regional climate models (RCMs) that were forced with a common set of reanalysis data created by running a climate model fed real-world data for a 20-year simulation period. The area analyzed was North America, where winter precipitation was the response variable and the 100-year extremum of daily winter precipitation was the test statistic, extreme values of which were estimated by fitting a tailed distribution to the data, taking into account their spatial aspects.

The six RCMs maintained similar general spatial patterns of extrema across North America, with the highest extremes in the Southeast and along the West Coast. However, when comparing absolute levels, which are most relevant to risk forecasts, the models exhibited strong disagreement. The lowest-predicting model was low almost everywhere in North America compared to the mean of the six models, and the highest-predicting model was above the mean almost everywhere. The difference between the two models was almost 60mm of daily precipitation for the 100-year extreme event over much of the United States. The other four models showed greatly differing spatial patterns of extremes from each other, and these differences were found to be statistically significant by an F-test. The researchers speculate that when driven by multiple GCMs rather than reanalysis data, the range of extreme outcomes would only increase.

Other studies have further demonstrated the difficulties models have in simulating extreme precipitation properties and trends. Kiktev *et al.* (2007), for example, analyzed the abilities of five global coupled climate models that played important roles in the IPCC's *Fourth Assessment Report* to simulate temporal trends over the second half of the twentieth century for five annual indices of precipitation extremes. Their results revealed "low skill" or an "absence" of model skill.

More of the same was reported by O'Gorman and Schneider (2009), who assessed "how precipitation extremes change in simulations with 11 different climate models in the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) archive." Based on their findings, as well as those of others, O'Gorman and Schneider report, "in simulations with comprehensive climate models, the rate of increase in precipitation extremes varies widely among models, especially in the tropics (Kharin *et al.,* 2007)." They also note, "the variations among models in the tropics indicate that simulated precipitation extremes may depend sensitively on the parameterization of unresolved and poorly understood processes," citing the work of Wilcox and Donner (2007). They find, "climate models do not correctly reproduce the interannual variability of precipitation extremes in the tropics (Allan and Soden, 2008), or the frequency and intensity distribution of precipitation generally (Wilcox and Donner, 2007; Dai, 2006; Sun *et al.,* 2006)." Thus the two researchers conclude, "current climate models cannot reliably predict changes in tropical precipitation extremes," noting "inaccurate simulation of the upward velocities may explain not only the intermodal scatter in changes in tropical precipitation extremes but also the inability of models to reproduce observed interannual variability."

Noting "a number of articles in the media and reports by some non-governmental organizations have suggested an increasing number of heavy precipitation events over portions of the western United States and have proposed that anthropogenic global warming could be the cause," Mass *et al.* (2011) analyzed "trends in heavy precipitation for the period 1950–2009 by examining the decadal distributions of the top 60, 40 and 20 two-day precipitation events for a collection of stations along the coastal zone of the United States and British Columbia [Canada], as well as the decadal distribution of maximum daily discharge for unregulated rivers from northern California to Washington State."

The three researchers from the University of Washington's Department of Atmospheric Sciences report their findings showed "during the past 60 years there has been a modest increase in heavy precipitation events over southern and central coastal California, a decline in heavy events from northern California through the central Oregon coast, a substantial increase in major events over Washington, and a modest increase over coastal British Columbia." However, they note, "most of these trends are not significantly different from zero at the 95% level." In addition, they found "trends in maximum daily discharge of unregulated rivers are consistent with the above pattern, with increasing discharges over the past three decades over Washington and northern Oregon and declines over the remainder of Oregon and northern California."

With respect to how consistent these results are with what climate models suggest should occur in response to rising temperatures, Mass *et al*. report the results of the two climate models analyzed by Chen *et al*. (2003) suggest "a pattern quite different from the one described above," and they state the model employed by Kim (2005) also produced "a pattern quite distinct from that observed since 1950." In addition, they note the models studied by Tebaldi *et al*. (2006) produced "a pattern closer, but not identical to, that observed over the past 60 years," and Duffy *et al*. (2006) "analyzed the precipitation produced over the western United States by four regional climate models," finding the spatial distributions of precipitation they produced to "vary substantially," even among themselves.

Mass *et al*. conclude, "considering the large variability in precipitation trends among the various general circulation models in the above studies and their associated regional climate models, and the differences between the simulated trend distributions and the observed trend patterns found in this study and others, it is unclear whether anthropogenic global warming is the source of past spatial patterns of extreme precipitation trends along the west coast of North America."

Mishra *et al*. (2012) point out "about half of the human population lives in urban areas (Martine *et al*., 2007), in contrast with only about 10 percent a century ago (Grimm *et al*., 2008)." Therefore, they note, "changes in extreme precipitation as the climate warms may pose challenges for stormwater management in urban areas, because most stormwater infrastructure was designed under the assumption of stationary climate that is 'dead' as argued by Milly *et al*. (2008)."

In an effort to better assess both the likelihood and significance of this potential problem, Mishra *et al*. compared precipitation output from all regional climate models that participated in the North American Regional Climate Change Assessment Program (NARCCAP), described by Mearns *et al*.

(2009), with observations made at 100 urban U.S. weather stations with data for the period 1950–2009. This work involved two distinct RCM simulations: one forced by output from the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis (Kanamitsu *et al*., 2002) for the period 1979–2000, and one forced by selected global circulation models that provided RCM boundary conditions for the period 1968–2000.

The analysis showed, "for most urban areas in the western and southeastern U.S.," in the words of the three scientists, "the seasonality of 3-hour precipitation extremes was not successfully reproduced by the RCMs with either reanalysis or GCM boundary conditions," because "the RCMs tended to predict 3-hour precipitation maxima in winter, whereas the observations indicated summer." The authors also report the RCMs "largely underestimated 3-hour precipitation maxima means and 100-year return period magnitudes at most locations across the United States for both reanalysis and GCM boundary conditions." For both 3- and 24-hour annual precipitation maxima, they write, "RCMs with reanalysis boundary conditions underestimated interannual variability" while they "overestimated interannual variability with GCM boundary conditions."

With respect to the ultimate utility of the RCM projections, Mishra *et al*. state performance deemed acceptable for stormwater infrastructure design was adequate at only about 25 percent of the urban areas. Regardless of boundary conditions, they note, "RCM-simulated 3-hour precipitation maxima at a 100-year return period could be considered acceptable for stormwater infrastructure design at less than 12% of the 100 urban areas."

Khoi and Suetsugi (2012) write "many general circulation models (GCMs) consistently predict increases in frequency and magnitudes of extreme climate events and variability of precipitation (IPCC, 2007)," noting "this will affect terrestrial water resources in the future, perhaps severely (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Chen *et al*., 2011)." Therefore, they conducted a study to see what aspect of the climate modeling enterprise led to the greatest degree of uncertainty in predicting rates of streamflow in Vietnam's Be River Catchment. The climate scenarios investigated by Khoi and Suetsugi were generated from seven different CMIP3 GCMs—CCCMA CGCM3.1, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM3.0, UKMO HadGEM1, UKMO Had CM3—using SRES emission scenarios A1B, A2, B1, and B2, along with prescribed increases in global mean temperature ranging from 0.5 to 6°C.

The two Vietnamese researchers report finding "the greatest source of uncertainty in impact of climate change on streamflow is GCM structure (choice of GCM)." They say this result "is in accordance with findings of other authors who also suggest that the choice of the GCM is the largest source of uncertainty in hydrological projection," citing Kingston and Taylor (2010), Kingston *et al*. (2011), Nobrega *et al*. (2011), Thorne (2011), and Xu *et al*. (2011), adding the range of uncertainty could increase even further if the analysis employed a larger number of GCMs.

Khoi and Suetsugi say their findings indicate "single GCM or GCMs ensemble mean evaluations of climate change impact are unlikely to provide a representative depiction of possible future changes in streamflow."

In one other streamflow-based study, Lloyd (2010) notes the Breede River "is the largest in South Africa's Western Province, and plays a significant part in the province's economy," and "models predict that flows into it could be seriously affected by climate change." More specifically, he reports Steynor *et al*. (2009) used "a form of neural network" "trained on historical climate data" that were "linked to historical flow data at five stations in the Breede River valley" in order to "downscale from a global climate model to the typical area of a catchment" and thereby determine the consequences of predicted future global warming for Breede River flows. That analysis projected Breede River flows would decrease if temperatures rise as predicted by climate models over the next 60 years.

As a check upon this approach to projecting the region's hydrologic future, Lloyd, a researcher at the Energy Institute of the Cape Peninsula University of Technology located in Cape Town, used flow data for five sites in the Breede Valley that had been maintained by the Department of Water Affairs to compute historical flow-rate trends over prior periods of warming ranging from 29 to 43 years in length.

All of the future flow-rates calculated by Steynor *et al*. exhibited double-digit negative percentage changes that averaged -25% for one global climate model and -50% for another global climate model. Similarly, the mean past trend of four of Lloyd's five stations was also negative (-13%). But the other station exhibited a positive trend (+14.6%). In addition, by "examination of river flows over the past 43 years in the Breede River basin," Lloyd was able to demonstrate that "changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows" of the negative-trend stations.

Interestingly, Steynor *et al*. had presumed warming would lead to *decreased* flow rates, as their projections suggested, and they thus assumed their projections were correct. Lloyd was able to demonstrate those results were driven primarily by unaccounted-for land use changes in the five catchments, and that in his newer study the one site with "a pristine watershed" was the one that had the "14% increase in flow over the study period," which was "contrary to the climate change predictions" and indicative of the fact that "climate change models cannot yet account for local climate change effects." Lloyd concludes "predictions of possible adverse local impacts from global climate change should therefore be treated with the greatest caution" and, "above all, they must not form the basis for any policy decisions until such time as they can reproduce known climatic effects satisfactorily."

Van Haren *et al*. (2013) write "estimates of future changes in extremes of multi-day precipitation sums are critical for estimates of future discharge extremes of large river basins and changes in [the] frequency of major flooding events," citing Kew *et al*. (2010). They indicate "a correct representation of past changes is an important condition to have confidence in projections for the future."

In an attempt to achieve some of that all-important confidence, van Haren *et al*. investigated changes in multi-day precipitation extremes in late winter in Europe and the Rhine river basin over the past 60 years using daily precipitation data and "the state-of-the-art gridded high resolution (0.5°) precipitation fields of the European ENSEMBLES project version 7.0 (Haylock *et al*. 2008)," where "observations [were] averaged to the same regular 1.5° grid when compared directly with the model results."

The four researchers report the climate models "underestimate the trend in extreme precipitation in the northern half of Europe" because they "underestimate the change in circulation over the past century and as a result have a much smaller (extreme) precipitation response." More specifically, they state "a dipole in the sea-level pressure trend over continental Europe causes positive trends in extremes in northern Europe and negative trends in the Iberian Peninsula," while "climate models have a much weaker pressure trend dipole and as a result a much weaker (extreme) precipitation response."

Van Haren *et al*. conclude their report by declaring "it is important that we improve our understanding of circulation changes, in particular related to the cause of the apparent mismatch between observed and modeled circulation trends over the past century," citing Haarsma *et al*. (2013).

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1.3.6 Temperature

How much of the warming of the past 100 years is due to human activity? When multiple forcings are varying and poorly characterized, and there is also internal variation, this question is more difficult, if not impossible, to answer. Nevertheless, several studies have attempted to do so

1.3.6.1 Surface and Near-Surface

Citing the work of Folland *et al*. (2001), Robinson *et al*. (2002), and Pan *et al*. (2004), Kunkel *et al*. (2006) note there was a lack of warming throughout the central and southeastern United States over the course of the twentieth century, dubbed a "warming hole" by the latter set of investigators. For an area they denote the Central United States (CUS), which they described as "one of the most agriculturally productive regions of the world and roughly defined around what is known as the 'Corn Belt'," Kunkel *et al*. used a data set of 252 surface climate stations with less than 10 percent missing temperature data over the period 1901–1999 to construct the CUS temperature time series plotted in Figure 1.3.6.1.1, where mean global temperature as determined by Hansen *et al*. (2001) is also plotted. Then, for comparative purposes, they examined 55 coupled general circulation model (CGCM) simulations driven by "modern estimates of time-varying forcing" plus 19 preindustrial unforced simulations, all derived from 18 CGCMs.

It is obvious, as shown in Figure 1.3.6.1.1, that the Central U.S. twentieth century temperature series is vastly different from that of the globe as a whole, at least as the latter is represented by Hansen *et al*. Rather than the final temperature of the twentieth century being warmer than the rest of the century, for this region it was more than 0.7°C cooler than it was a mere 65 years earlier. In addition, Kunkel *et al*. report "the warming hole is not a robust response of contemporary CGCMs to the estimated external forcings."

Kiktev *et al*. (2007) introduce their study by stating the importance of "comparing climate modeling results with historical observations … to further develop climate models and to understand the capabilities and limitations of climate change projections." They analyzed the abilities of five global coupled climate models that played important roles in the IPCC's *Fourth Assessment Report* to simulate temporal trends over the second half of the twentieth century of five annual indices of extremes in surface temperature—annual percentage of days with T_{min} < 10th percentile, with T_{max} < 10th percentile, with T_{min} > 90th percentile, with T_{max} > 90th percentile, and annual number of frost days, i.e., T_{min} < 0°C—as well as five annual indices of extremes in precipitation, the observational data for which they obtained from the HadEX global data set that contains gridded annual and seasonal values of the ten extreme indices calculated from series of *in situ* daily measurements (Alexander *et al*., 2006). The international research team, hailing from Australia, Japan, Russia, and the United Kingdom, state "the results mostly show moderate skill for temperature indices."

In an effort "to distinguish between simultaneous natural and anthropogenic impacts on surface temperature, regionally as well as globally," Lean and Rind (2008) performed "a robust multivariate analysis using the best available estimates of each together with the observed surface temperature record from 1889 to 2006." They report, "contrary to recent assessments based on theoretical models (IPCC, 2007) the anthropogenic warming estimated directly from the historical observations is more pronounced between 45°S and 50°N than at higher latitudes," which, in their words, "is the approximate inverse of the model-simulated anthropogenic plus natural temperature trends ... which have minimum values in the tropics and increase steadily from 30 to 70°N." Furthermore, they continue, "the empirically-derived zonal mean anthropogenic changes have approximate hemispheric symmetry whereas the mid-to-high latitude modeled changes are larger in the Northern hemisphere." The two researchers conclude "climate models may therefore lack—or incorrectly parameterize—fundamental processes by which surface temperatures respond to radiative forcings."

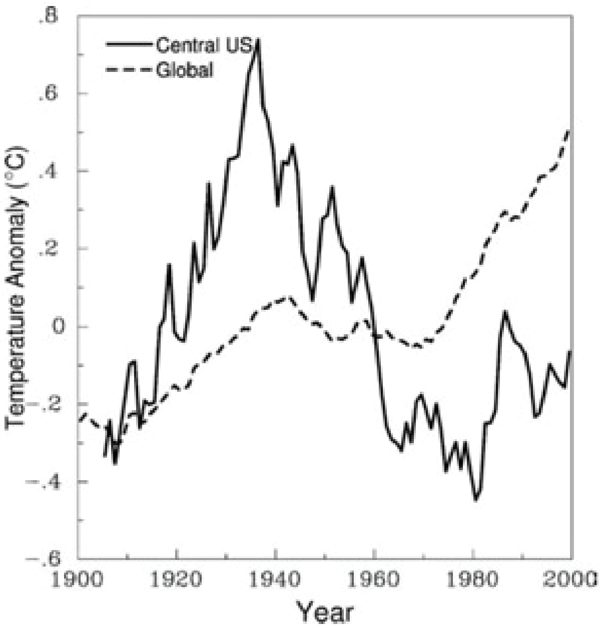

Figure 1.3.6.1.1. Twentieth-century Central United States and mean global temperature anomalies. Reprinted with permission from Kunkel, K.E., Liang, X.-Z., Zhu, J., and Lin, Y. 2006. Can CGCMs simulate the twentieth-century "warming hole" in the central United States? *Journal of Climate* **19**: 4137–4153.

Chylek *et al.* (2009) point out "one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback." More specifically, they say, "the surface air temperature change in the Arctic is predicted to be about two to three times the global mean," citing the IPCC (2007). In conducting their own study, the authors utilized Arctic surface air temperature data from 37 meteorological stations north of 64°N in an effort to explore the latitudinal variability in Arctic temperatures within two belts—the low Arctic (64°N-70°N) and the high Arctic (70°N-90°N)—comparing them with mean global air temperatures over three sequential periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

The five researchers report, "the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean." More precisely, the Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that is the end of the real world's climate-change agreement with theory. During the 1910–1940 warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic. Such findings constitute another important example of the principle described by Reifen and Toumi (2009): that a model that performs well for one time period will not necessarily perform well for another.

Expounding on this principle, Reifen and Toumi (2009) note, "with the ever increasing number of models, the question arises of how to make a best estimate prediction of future temperature change." That is to say, which model should one use? With respect to this question, they note, "one key assumption, on which the principle of performance-based selection rests, is that a model which performs better in one time period will continue to perform better in the future." In other words, if a model predicts past climate fairly well, it should predict future climate fairly well. The principle sounds reasonable enough, but does it hold true?

Reifen and Toumi examined this question "in an observational context" for what they describe as "the first time." Working with the 17 climate models employed by the IPCC in its *Fourth Assessment Report*, they determined how accurately individual models, as well as subsets of the 17 models, simulated the temperature history of Europe, Siberia, and the entire globe over a selection period (such as 1900–1919) and a subsequent test period (such as 1920–1939), asking whether the results for the test period are as good as those of the selection period. They followed this procedure while working their way through the entire twentieth century at one-year time-steps for not only 20-year selection and test intervals but also for 10- and 30-year intervals.

The two researchers could find "no evidence of future prediction skill delivered by past performance-based model selection," noting, "there seems to be little persistence in relative model skill." They speculate "the cause of this behavior is the non-stationarity of climate feedback strengths," which they explain by stating, "models that respond accurately in one period are likely to have the correct feedback strength at that time," but "the feedback strength and forcing is not stationary, favoring no particular model or groups of models consistently." Given such findings, the U.K. physicists conclude their analysis of the subject by stating "the common investment advice that 'past performance is no guarantee of future returns' and to 'own a portfolio' appears also to be relevant to climate projections."

Also studying the Arctic, Liu *et al*. (2008) "assessed how well the current day state-of-the-art reanalyses and CGCMs [coupled global climate models] are reproducing the annual mean, seasonal cycle, variability and trend of the observed SAT [surface air temperature] over the Arctic Ocean for the late twentieth century (where sea ice changes are largest)." The results indicate "large uncertainties are still found in simulating the climate of the twentieth century," they write, and on an annual basis, "almost two thirds of the IPCC AR4 models have biases that [are] greater than the standard deviation of the observed SAT variability." Liu *et al*. further note the models "cannot capture the observed dominant SAT mode variability in winter and seasonality of SAT trends." The majority of the models "show an out-of-phase relationship between the sea ice area and SAT biases," they write, and "there is no obvious improvement since the IPCC *Third Assessment Report*."

Anagnostopoulos *et al.* (2010) evaluate the ability of models used by the IPCC to generate regional climates to reproduce observed climate and climate change, and they take issue with the IPCC's assessment of its models. They compare the output of these models to temperature and precipitation observations at 55 points worldwide. They then do a similar comparison for 70 points in the USA on several time scales. They selected the USA for the refined study because it has a dense network of surface stations. Thus, they can evaluate the model performance at the large scale and the regional scale.

In order to compare observed records to model projections, they use a statistical technique called "best linear unbiased estimation," comparing observations at a particular station and nearby stations to a linear combination of the model outputs and comparing the time series via traditional statistical measures.

The authors demonstrate, "At the monthly time scale the models generally reproduce the sequence of cold-warm and wet-dry periods at all stations examined." However, the results were much worse at the annual time scale and the variability in the general circulation is underestimated. For the climate time-scales, some of the grid points will show 30-year temperature rises in the model simulation, but the actual data shows temperature falls. This is similar for both the large and regional scales. Additionally, the models could not capture the long-term climate changes from 1890 to the end of the twentieth century at many of the points (Figure 1.3.6.1.2).

As Anagnostopoulos *et al.* state, "It is claimed that GCMs provide credible quantitative estimates of future climate change, particularly at continental times scales and above. Examining the local performance of the models at 55 points, we found that local projections do not correlate well with observed measurements." They found the model performance was actually worse on larger scales than on regional ones. They suggest the central issue is not about the performance of the GCMs, but whether climate can be predicted deterministically at all given the uncertainties inherent in the atmosphere.

Anagnostopoulos *et al.* use statistics to make the point others have made regarding models using dynamics. Anagnostopoulos *et al.* say there simply may not be a predictable "core" to the climate that is only obscured by layers of complexity or uncertainty. They also propose a shift in our modeling approach, suggesting statistical methods, in addition to dynamical methods and models, be used to generate future scenarios for climate as has been done successfully in other fields such as thermophysics or turbulence.

Lo and Hsu (2010) point out "widespread abrupt warming in the extratropical Northern Hemisphere occurred in the late 1980s" and say the warming was associated with a change in the relative influence of a Pacific Decadal Oscillation (PDO)-like pattern and an Arctic Oscillation (AO)-like pattern. Utilizing land surface temperature data obtained from the University of East Anglia's Climatic Research Unit (Mitchell *et al*., 2004), plus sea surface temperature data obtained from the U.K.'s Meteorological Office (Rayner *et al*., 2003), the authors explored the nature of this temperature increase and tested the ability of IPCC/CMIP3 models to simulate it.

The two Taiwanese researchers report the "accelerated warming in the Northern Hemisphere" was related to the emergence of an AO-like pattern in the late 1980s and the concomitant weakening of the previously prevailing PDO-like pattern occurring in tandem. These results they say, , together with results obtained from current IPCC/CMIP3 models, "do not support the scenario that the emerging influence of the AO-like pattern in the 1980s can be attributed to the anthropogenic greenhouse effect." Lo and Hsu also conclude, "this study indicates the importance of the changing behavior of the decadal fluctuations in the recent climate regime shift," and they highlight

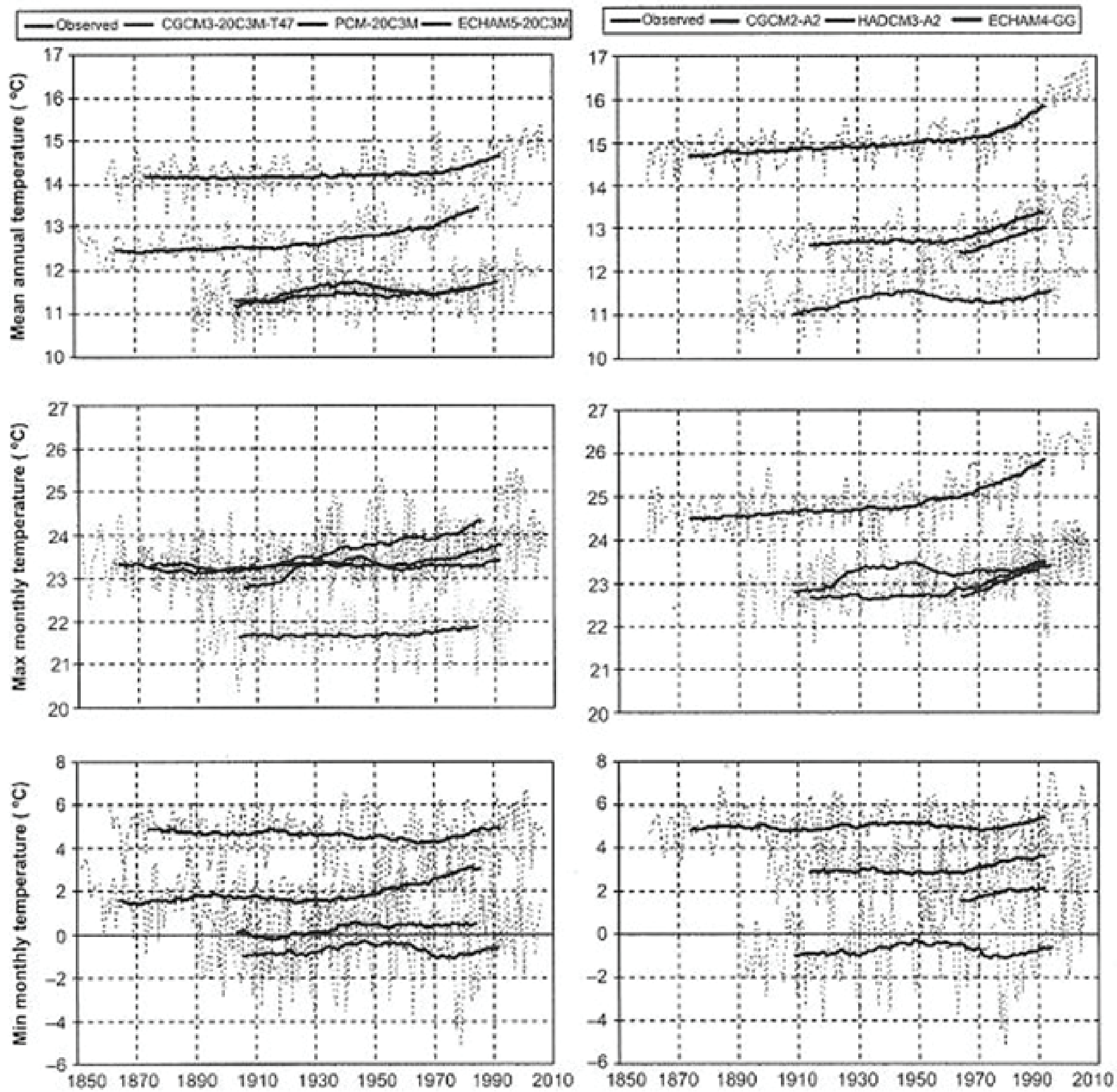

Figure 1.3.6.1.2. The observed and model temperature time series integrated over the USA (annual means and maximum and minimum monthly) for the annual and 30-year time scales. Adapted from Anagnostopoulos, G.G., Koutsoyiannis, D., Christofides, A., Efstradiadis, A., and Mamassis, N. 2010. A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal* **55**: 1094–1110, Figure 12.

what they call "the insufficient capability of the present state-of-the-art IPCC/CMIP3 models in simulating this change."

DelSole *et al.* (2011) used a set of climate models run in "control" or unforced mode to develop a 300-year data set of spatial ocean temperature data, where it was found that an internal pattern, detectable using a spatial fingerprinting technique, could be identified in the simulated data. This spatial pattern of ocean temperature anomalies was labeled the Internal Multidecadal Pattern (IMP). It was found to be highly coherent with the Atlantic Multidecadal Oscillation (AMO), suggesting the models were able to match the internal dynamics of the real-Earth system reasonably well. The researchers next extracted, also by means of discriminant fingerprinting, the forced component of the spatial patterns produced in the absence of the IMP as an orthogonal function, which they demonstrated has only a minor effect (less than 1/7 the amplitude) on the IMP. They then used historical sea surface temperature data to evaluate the relative importance of the forced vs. IMP components of change since 1850.

In considering the latter portion of the record

(1946–2008), the results indicate the internal variability component of climate change (the IMP) operated in a cooling mode between 1946 and 1977, but switched thereafter to a warming mode between 1977 and 2008, suggesting the IMP is strong enough to overwhelm any anthropogenic signal during this latter period of time. They also note "the trend due to only the forced component is statistically the same in the two 32-year periods and in the 63-year period." That is to say, the forced part was not accelerating. Taken together, these results imply the observed trend differs between the periods 1946–1977 and 1977–2008 not because the forced response accelerated but because "internal variability led to relative cooling in the earlier period and relative warming in the later period." Their results suggest simple extrapolations of rates of warming from 1980 onward overestimate the forced component of warming, and therefore using this period without factoring out internal variability will likely lead to unrealistic values of climate sensitivity.

Lavers *et al.* (2009), in a study described previously in Section 1.4.5.1, assessed the predictability of monthly "retrospective forecasts," or hindcasts, composed of multiple nine-month projections initialized during each month of the year over the period 1981–2001, comparing the projections against real-world air temperatures obtained from ERA-40 reanalysis data. In addition, they conducted a virtual-world analysis where the output of one of the models was arbitrarily assumed to be the truth and the average of the rest of the models was assumed to be the predictor.

The researchers report that in the virtual world of the climate models, there was quite good skill over the first two weeks of the forecast, when the spread of ensemble model members was small, but there was a large drop-off in predictive skill in the second 15-day period. Things were worse in the real world, where they say the models had negligible skill over land at a 31-day lead time, "a relatively short lead time in terms of seasonal climate prediction." The three researchers conclude, "it appears that only through significant model improvements can useful long-lead forecasts be provided that would be useful for decision makers," a quest they state "may prove to be elusive."

Crook and Forster (2011) note "predicting our future influence on climate requires us to have confidence in the climate models used to make predictions, and in particular that the models' climate sensitivity and ocean heat storage characteristics are realistic." They go on to say that confidence may be gained "by assessing how well climate models reproduce current climatology and climate variability, and how their feedback parameters compare with estimates from observations."

Using the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) and real-world data from the HadCRUT3 database, Crook and Forster first determined "the surface temperature response contributions due to long-term radiative feedbacks, atmosphere-adjusted forcing, and heat storage and transport for a number of coupled ocean-atmosphere climate models," after which they compared "the linear trends of global mean, Arctic mean and tropical mean surface temperature responses of these models with observations over several time periods." They also investigated "why models do or do not reproduce the observed temperature response patterns" and performed "optimal fingerprinting analyses on the components of surface temperature response to test their forcing, feedback and heat storage responses."

The two University of Leeds (U.K.) researchers found tropical twentieth century warming was too large and Arctic amplification too low in the Geophysical Fluid Dynamics Laboratory CM2.1 model, the Meteorological Research Institute CGCM232a model, and the MIROC3(hires) model "because of unrealistic forcing distributions." They also determined "the Arctic amplification in both National Center for Atmospheric Research models is unrealistically high because of high feedback contributions in the Arctic compared to the tropics." In addition, they report, "few models reproduce the strong observed warming trend from 1918 to 1940," noting "the simulated trend is too low, particularly in the tropics, even allowing for internal variability, suggesting there is too little positive forcing or too much negative forcing in the models at this time."

According to Miao *et al*. (2012), the accuracy of any GCM "should be established through validation studies before using it to predict future climate scenarios." "Although accurate simulation of the present climate does not guarantee that forecasts of future climate will be reliable," they write, "it is generally accepted that the agreement of model predictions with present observations is a necessary prerequisite in order to have confidence in the quality of a model."

Working within this conceptual framework, Miao *et al*. assessed the performance of the AR4 GCMs, otherwise known as the CMIP3 models, in simulating precipitation and temperature in China from 1960 to 1999, comparing the model simulations with observed data using "system bias (*B*), root-mean-square error (*RMSE*), Pearson correlation coefficient (*R*) and Nash-Sutcliffe model efficiency (*E*)" as evaluation metrics.

The four researchers find certain of the CMIP3 models "are unsuitable for application to China, with little capacity to simulate the spatial variations in climate across the country," adding that all of them "give unsatisfactory simulations of the inter-annual temporal variability." In addition, they find "each AR4 GCM performs differently in different regions of China." Miao *et al*. conclude "the inter-annual simulations (temperature and precipitation) by AR4 GCMs are not suitable for direct application" and "caution should be applied when using outputs from the AR4 GCMs in hydrological and ecological assessments" due to their "poor performance."

According to Morak *et al*. (2013), studies of observational temperature records over the past 50 to 100 years have found evidence for increases in both mean and extreme (maximum and minimum) near-surface air temperatures, but they note the increase in maximum temperature has been of smaller magnitude than the increase in minimum temperature. This state of affairs has led to a decrease in the diurnal temperature range. They compared "observed and climate model-simulated trends in mean values of temperature extreme indices, splitting the year into the dynamically active boreal cold (ONDJFM) and warm (AMJJAS) seasons." To do so, they used "modeled daily minimum and maximum surface temperature data derived from simulations with the Hadley Centre Global Environmental Model, version 1 (HadGEM1)."

The three U.K. researchers report, among other findings, that the model "significantly underestimates changes in some regions, particularly in winter across large parts of Asia" and "has a tendency to overestimate changes in the frequency of hot days in both the [a] winter and [b] summer seasons over [d] most regions, and in the [e] global and [f] hemispheric mean." The model "also overestimates changes in the frequency of warm winter days on larger scales." With respect to changes in cold extremes the model "does underestimate them in some regions" and "there are some regions with trends of the opposite sign." In addition, Morak *et al.* "the particular regional trend pattern, often also referred to as the 'warming hole,' is not evident in the simulated trend pattern," citing Pan *et al*. (2004), Kunkel *et al*. (2006), Portmann *et al*. (2009), and Meehl *et al*. (2012). And they say "the model shows a tendency to significantly overestimate changes in warm daytime extremes, particularly in summer." Although the HadGEM1 does some things well, there are a number of other things it has yet to accomplish satisfactorily.

As the observed rate of rise in the global average temperature has slowed during recent decades, the gap between observations and climate models results has widened. The discrepancy is now so large as to indicate a statistically significant difference between the climate modeled trends and the observed trend. The existence of such a large discrepancy is a strong indication that climate models are failing in their ability to accurately capture known changes in this key parameter of Earth's climate system.

A clear demonstration the models are failing to contain observations was made by Knappenberger and Michaels (2013), who compiled the range of trends in surface temperatures during the first several decades of the twenty-first century projected by CMIP3 climate models running emissions scenario A1B. Knappenberger and Michaels placed the observed temperatures within this modeled distribution (see Figure 1.3.6.1.3). The observed trends lie very close to, and in some cases below, the lower bound of the 95% certainty range derived from climate model projections. Knappenberger and Michaels report "at the global scale, climate models are on the verge of failing to adequately capture observed changes in the average temperature over the past 10 to 30 years—the period of the greatest human influence on the atmosphere." They conclude, "It is impossible to present reliable future projections from a collection of climate models which generally cannot simulate observed change."

In the same vein, Fyfe *et al*. (2013) examined the performance of the newer CMIP5 climate models and found a similar result. The researchers "considered trends in global mean surface temperature computed from 117 simulations of the climate by 37 CMIP5 models." They note the "models generally simulate natural variability—including that associated with the El Niño–Southern Oscillation and explosive volcanic eruptions—as well as estimate the combined response of climate to changes in greenhouse gas concentrations, aerosol abundance (of sulphate, black carbon and organic carbon, for example), ozone concentrations (tropospheric and stratospheric), land use (for example, deforestation) and solar variability." But despite the models' claimed ability to simulate

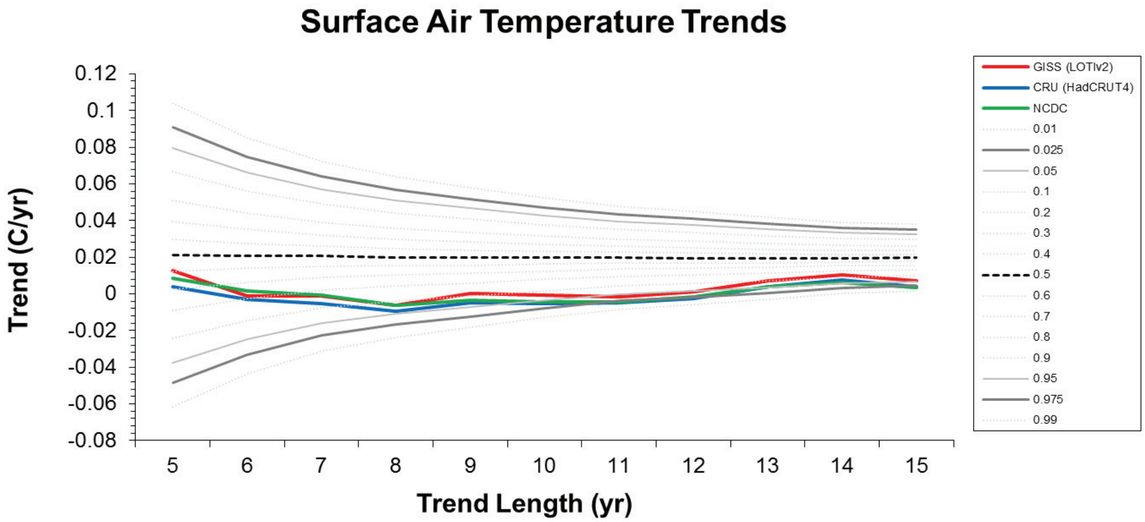

Figure 1.3.6.1.3. Trends (through 2012) in three observed global surface temperature records of length 5 to 15 years (colored lines) set against the probability (gray lines) derived from the complete collection of climate model runs used in the IPCC Fourth Assessment Report under the SRES A1B emissions scenario. Reprinted with permission from Knappenberger, P.C. and Michaels, P.J., 2013. Policy implications of climate models on the verge of failure. American Geophysical Union Science Policy Conference. Washington, DC, June 24–26, 2013.

both natural variability and human influences, when compared against actual observations, their simulation of the evolution of the global average temperature is flawed. Over the past 20 years (1993–2012), Fyfe *et al*. find the "rate of warming is significantly slower than that simulated by the climate models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5)" and "the inconsistency between observed and simulated global warming is even more striking for temperature trends computed over the past fifteen years (1998–2012)." They add, "It is worth noting that the observed trend over this period—not significantly different from zero—suggests a temporary 'hiatus' in global warming." Fyfe *et al*. conclude, "Ultimately the causes of this inconsistency will only be understood after careful comparison of simulated internal climate variability and climate model forcings with observations from the past two decades, and by waiting to see how global temperature responds over the coming decades."

The IPCC is in a very difficult position. In order to defend the CMIP5 suite of models, it must somehow argue they did *not* underpredict warming as the greatest increases in atmospheric carbon dioxide content occurred. Further, they must invalidate at least 19 separate experiments authored by 42 researchers in the citations noted earlier in this section.

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1.4.6.2 Mid- and Upper-Troposphere

Several studies have examined model treatment of processes in the troposphere. The testing of climate model results is an important but difficult problem. One of the key model results is the presence of a tropical troposphere “hotspot” in which the troposphere warms faster than the surface under conditions of enhanced greenhouse gas forcing. Previous studies have produced disagreement over whether data were consistent with models on this question. However, Christy *et al.* (2010) made several advances by enhancing the data for surface trends, extending the data to a 31-year length, evaluating the wind-based temperature estimates, and clarifying the meaning of “best estimate” multi-data warming trends from data and models.

Two prior studies had derived tropospheric temperature trends from the Thermal Wind Equation (TWE)—which uses radiosonde measurements of wind speed to calculate temperature—on the theoretical basis that warmer air should move faster than cooler air. They found there were biases in the data for this type of calculation. For example, particularly for older radiosonde observations, on days when the upper wind was stronger, the balloons would tend to blow out of receiver range. This created a bias by causing missing data for high winds for older observations, leading to a spurious warm trend over time. Overall, the TWE-based trends were three times greater than trends derived from all other types of data. In addition, they did not agree with other wind data and also were based on much sparser data. Radiosonde data were therefore not used in the Christy *et al*. analysis, which also identified a small warm bias in the Remote Sensing System (RSS) satellite data that was explained by Christy and his colleagues.

The next innovation was to use the Scaling Ratio (SR), the ratio of atmospheric temperature trend to surface temperature trend. The SR attempts to factor out the effect of the lack of actual (historic) El Niños or other oscillations in climate model runs, and such simulated events in different computer runs. Christy and his eight colleagues found the SR for real-world data was 0.8 ± 0.3, whereas the model simulations had a SR of 1.38 ± 0.08 (a significant difference). That is, the data show a lower rate of warming for the lower troposphere than for the surface (though not statistically different), whereas the models show amplification. The SR value for the middle troposphere data was 0.4, even more different from the model predictions. Only the SR for RSS data, which has a documented warming bias, overlaps with any model SR results. Given these findings, the work of Christy *et al.* suggests current state-of-the-art climate models are fundamentally wrong in how they represent this portion of Earth's atmosphere.

The tropical troposphere also was the focus of study for Fu *et al*. (2011), who note the IPCC *Fourth Assessment Report* (AR4) general circulation models "predict a tropical tropospheric warming that increases with height, reaches its maximum at ~200 hPa, and decreases to zero near the tropical tropopause." They add, "this feature has important implications to the climate sensitivity because of its impact on water vapor, lapse rate and cloud feedbacks and to the change of atmospheric circulations." Therefore, they write, it is "critically important to observationally test the GCM-simulated maximum warming in the tropical upper troposphere."

Fu *et al*. thus examined trends in the temperature difference (ΔT) between the tropical upper- and lower-middle-troposphere based on satellite microwave sounding unit (MSU) data, as interpreted by University of Alabama at Huntsville (UAH) and RSS teams, comparing both sets of results with AR4 GCM ΔT simulations for the period 1979–2010.

The three researchers report the RSS and UAH ΔT time series "agree well with each other" and showed little trend over the period of record. By contrast, they note there is "a steady positive trend" in the model-simulated ΔT results, concluding the significantly smaller ΔT trends from both the RSS and UAH teams "indicate possible common errors among AR4 GCMs." In addition, they note the tropical surface temperature trend of the multi-model ensemble mean is more than 60% larger than that derived from observations, "indicating that AR4 GCMs overestimate the warming in the tropics for 1979–2010."

In addition to greatly overestimating the tropical surface temperature trend, Fu *et al*. note, "it is evident that the AR4 GCMs exaggerate the increase in static stability between [the] tropical middle and upper troposphere during the last three decades."

One year later, Po-Chedley and Fu (2012) write, "recent studies of temperature trend amplification in the tropical upper troposphere relative to the lower-middle troposphere found that coupled atmosphere-ocean models from CMIP3 exaggerated this amplification compared to satellite microwave sounding unit (Fu *et al*., 2011) and radiosonde (Seidel *et al*., 2012) observations." The two authors "revisit this issue using atmospheric GCMs with prescribed historical sea surface temperatures (SSTs) and coupled atmosphere-ocean GCMs that participated in the latest model intercomparison project, CMIP5."

The pair of researchers report their work demonstrated "even with historical SSTs as a boundary condition, most atmospheric models exhibit excessive tropical upper tropospheric warming relative to the lower-middle troposphere as compared with satellite-borne microwave sounding unit measurements." In addition, they note, "the results from CMIP5 coupled atmosphere-ocean GCMs are similar to findings from CMIP3 coupled GCMs."

Focusing more on the mid-troposphere, Handorf *et al*. (2012) write, "atmospheric teleconnections describe important aspects of the low-frequency atmospheric variability on time-scales of months and longer," adding "in light of the increased need to provide reliable statements about seasonal to decadal predictability, it is necessary that state-of-the-art climate models simulate the spatial and temporal behavior of atmospheric teleconnections satisfactorily." Therefore, they continue, "an evaluation of climate models requires the evaluation of the simulated climate variability in terms of teleconnection patterns." Handorf and Dethloff evaluated "the ability of state-of-the-art climate models to reproduce the low-frequency variability of the mid-tropospheric winter flow of the Northern Hemisphere in terms of atmospheric teleconnection patterns." To do so, they used the CMIP3 multimodel ensemble for the period 1958–1999, for which reliable reanalysis data were available for comparison.

The two researchers conclude, "current state-of-the-art climate models are not able to reproduce the temporal behavior, in particular the exact phasing of the dominant patterns due to internally generated model variability." In addition, they write, "the state-of-the-art climate models are not able to capture the observed frequency behavior and characteristic time scales for the coupled runs satisfactorily ... in accordance with Stoner *et al*. (2009) and Casado and Pastor (2012)," both of which studies conclude, in their words, that "the models are not able to reproduce the temporal characteristics of atmospheric teleconnection time-series."

"In light of the strong need to provide reliable assessments of decadal predictability," Handorf and Dethloff additionally state "the potential of atmospheric teleconnections for decadal predictability needs further investigations" that "require a better understanding of [1] the underlying mechanisms of variability patterns and flow regimes, [2] an improvement of the skill of state-of-the-art climate and Earth system models in reproducing atmospheric teleconnections and [3] the identification of sources for long-range predictive skill of teleconnections."

In other research, Santer et al. (2011) examined the consistency between satellite observations of the lower troposphere and climate model simulations of that atmospheric region. The 17 researchers set the average of the observed temperature trends of lengths varying from 10 to 32 years against the distribution of the same trend as simulated by a collection of CMIP3 climate models (see Figure 1.4.6.2.1). While the lower troposphere temperature trends (TLT) "in the observational satellite datasets are not statistically unusual relative to model-based distributions of externally forced TLT trends" they found "it should be qualified by noting that: 1) The multi-model average TLT trend is always larger than the average observed TLT trend" and "2) As the trend fitting period increases … average observed trends are increasingly more unusual with respect to the multi-model distribution of forced trends." Put another way, over longer periods of time that include a more robust signal, the discrepancy between model simulations and observed trends in the temperature of the lower troposphere increases, with the model overestimates being on the verge of statistical significance.

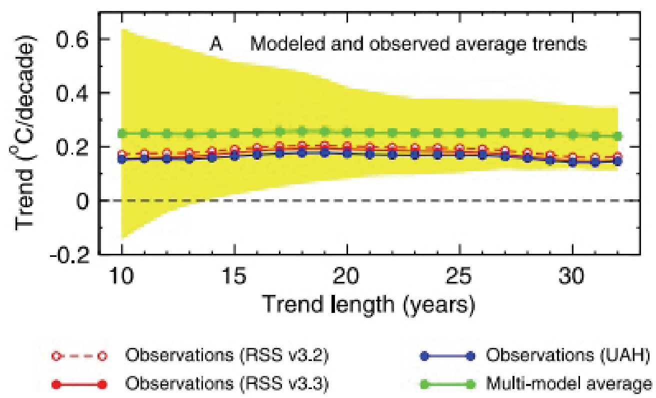

Figure 1.4.6.2.1. A comparison between modeled and observed trends in the average temperature of the lower atmosphere, for periods ranging from 10 to 32 years (during the period 1979 through 2010). The yellow is the 5-95 percentile range of individual model projections, the green is the model average, the red and blue are the average of the observations, as compiled by Remote Sensing Systems and University of Alabama in Huntsville respectively. Adapted from Santer, B.D., Mears, C., Doutriaux, C., Caldwell, P., Gleckler, P.J., Wigley, T.M.L., Solomon, S., Gillett, N.P., Ivanova, D., Karl, T.R., Lanzante, J.R., Meehl, G.A., Stott, P.A., Taylor, K.E., Thorne, P.W., Wehner, M.F., and Wentz, F.J. 2011. Separating signal and noise in atmospheric temperature changes: the importance of timescale. *Journal of Geophysical Research* **116**: 10.1029/ 2011JD016263.

Santer *et al*. (2013) performed "a multimodel detection and attribution study with climate model simulation output and satellite-based measurements of tropospheric and stratospheric temperature change," using "simulation output from 20 climate models participating in phase 5 of the Coupled Model Intercomparison Project," which "provides estimates of the signal pattern in response to combined anthropogenic and natural external forcing and the noise of internally generated variability." Among other things, the 21 researchers report "most models do not replicate the size of the observed changes," in that "the models analyzed underestimate the observed cooling of the lower stratosphere and overestimate the warming of the troposphere," where warming, in their opinion (Santer *et al*., 2003; Hansen *et al*., 2005), "is mainly driven by human-caused increases in well-mixed greenhouse gases," and where "CMIP5 estimates of variability on 5- to 20-year timescales are (on average) 55-69% larger than in observations."

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1.3.7 Oceans

The vast majority of the surface of the planet consists of oceans, which play a significant role in the modulation and control of Earth's climate. As is true of other factors we have previously discussed, modeling of the oceans has proved to be a difficult task.

1.3.7.1 Atlantic Ocean

Keeley *et al*. (2012) note, "current state-of-the-art climate models fail to capture accurately the path of the Gulf Stream and North Atlantic Current," and this model failure "leads to a warm bias near the North American coast, where the modeled Gulf Stream separates from the coast further north, and a cold anomaly to the east of the Grand Banks of Newfoundland, where the North Atlantic Current remains too zonal."

Using a high-resolution coupled atmosphere-ocean model (HiGEM), described in detail by Shaffrey *et al*. (2009), Keeley *et al*. analyzed the impacts of the sea surface temperature (SST) biases created by the model in the North Atlantic in winter—approximately 8°C too cold to the east of the Grand Banks of Newfoundland and 6°C too warm near the east coast of North America—on the mean climatic state of the North Atlantic European region, along with the variability associated with those model-induced SST biases.

The three UK researchers say their results indicate the model-induced SST errors produce a mean sea-level pressure response "similar in magnitude and pattern to the atmospheric circulation errors in the coupled climate model." They also note "errors in the coupled model storm tracks and North Atlantic Oscillation, compared to reanalysis data, can also be explained partly by these SST errors." Keeley *et al*. conclude, "both [1] the error in the Gulf Stream separation location and [2] the path of the North Atlantic Current around the Grand Banks play important roles in affecting the atmospheric circulation"; they further note "reducing these coupled model errors could improve significantly the representation of the large-scale atmospheric circulation of the North Atlantic and European region."

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1.3.7.2 Pacific Ocean

Thompson and Kwon (2010) used a state-of-the-art coupled-atmosphere-ocean general circulation model known as the Community Climate System Model version 3 (CCSM3) to demonstrate that climate models have difficulty simulating interdecadal variations in the Pacific Ocean Circulation. The authors used the model with atmospheric radiative forcing fixed to 1990 levels and with medium-scale grid resolution. The model output was run for 700 years and a 100-year slice was selected starting with year 500.

The model was unable to capture the natural characteristics of the Kuroshio Current and its extension (KE), resulting in a poor representation of climate variability in the North Pacific region. In nature, the mean position of the KE and the strongest sea surface temperature (SST) gradients are typically separated by 500 km. In the model control run, the two phenomena were coincident, resulting in excessively strong SST variations (Figure 1.3.7.2.1).

The Kuroshio Current, like its Atlantic counterpart, the Gulf Stream, is a strong, narrow current in the Northwest Pacific that runs along Japan and continues into the North Pacific. The Oyashio Extension (OE) is a distinct current running along the Kurile Islands and Hokkaido. This current is analogous to the Labrador Current along Northeast North America. In the model, there was only one broad current, weaker than what is observed in nature. As a result, the SSTs are too warm near the Japan coast and too cold into the Pacific. The long-term SST variations were also too strong in the model.

Interdecadal climate variations are internal forcings to Earth's atmosphere system that, in concert with external forcing, will be important in determining what our future climate may look like. In order to create reasonable scenarios of climate change, these phenomena must be modeled accurately. Their strength and intensity also must be put into proper context with that of the total natural and greenhouse forcing in order to attribute the source of climate change.

Many studies have shown the importance of SST gradients in contributing to the occurrence, strength, and location of atmospheric phenomena such as jet streams, storm tracks, and blocking (e.g., Kung *et al.* 1990; 1992; 1993). These phenomena, as well as the ocean circulations, are important in transporting heat and momentum poleward and maintaining the general circulation. Thus the reliability and accuracy of regional climate change model scenarios far from the Pacific (e.g., agriculturally important continental regions) will be strongly influenced by the model's ability to capture Pacific region atmosphere and ocean circulations.

As policymakers use climate simulations for the creation of policy and for planning purposes, it is important that biases in the climate models be acknowledged and understood. As Thompson and Kwon (2010) write, "it is important to note that CCSM3 is not unique in its poor representation of the KOE. The diffuse front and lack of distinction between the OE and KE is typical of low-resolution climate models."

In a paper published in the *Journal of Geophysical Research*, Guemas *et al*. (2012) also focused on this region of the Pacific Ocean, writing "the North Pacific region has a strong influence on North American and Asian climate." They also state it is "the area with the worst performance in several state-of-the-art decadal climate predictions" and add that the failure of essentially all climate models "to

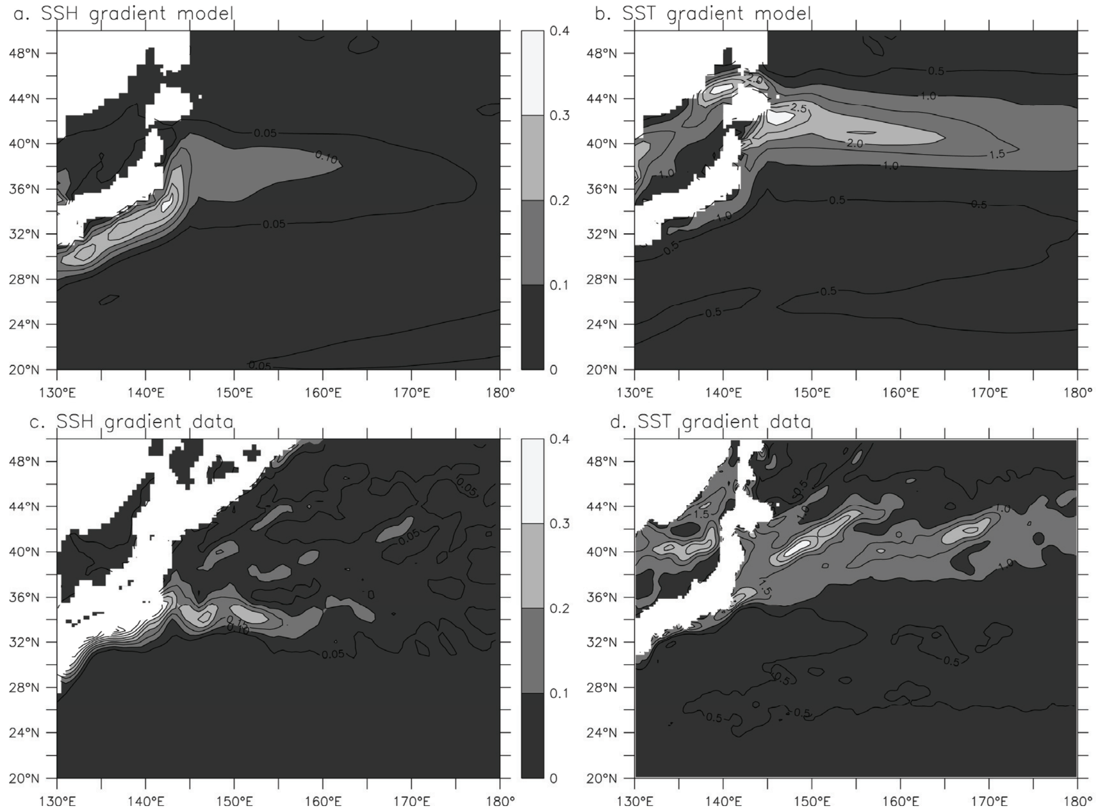

Figure 1.3.7.2.1. The gradients of sea surface height (SSH) and SST for the (a) and (b) control run—CCSM3, (c) generated by Maximenko and Niiler (2004), and (d) National Oceanic and Atmospheric Administration (NOAA). Reprinted with permission from Thompson, L. and Y.O. Kwon, 2010: An enhancement of Low-Frequency Variability in the Kuroshio-Oyashio Extension in CCM3 owing to Ocean Model Biases. *Journal of Climate* **23,** 6221-6233. DOI:10.1175/2010JCLI3402.1, Figure 1.

represent two major warm sea surface temperature events occurring around 1963 and 1968 largely contributes to this poor skill," noting "understanding the causes of these major warm events is thus of primary concern to improve prediction of North Pacific, North American and Asian climate."

The five researchers investigated "the reasons for this particularly low skill," identifying and describing the two major warm events they say have been "consistently missed by every climate forecast system." Based on their study of 11 observational data sets, Guemas *et al*. suggest the 1963 warm event "stemmed from the propagation of a warm anomaly along the Kuroshio-Oyashio extension" and the 1968 warm event "originated from the upward transfer of a warm water mass centered at 200 meters depth." They conclude, "biases in ocean mixing processes present in many climate prediction models seem to explain the inability to predict these two major events."

Although they acknowledge "reducing systematic biases in ocean stratification and improving the representation of ocean mixing processes has been a long-standing effort," Guemas *et al*. say their findings suggest allocating still more resources to "improving simulation of ocean mixing has the potential to significantly improve decadal climate prediction."

Furtado *et al*. (2011) note the North Pacific Decadal Variability (NPDV) "is a key component in predictability studies of both regional and global climate change," adding that "two patterns of climate variability in the North Pacific generally characterize NPDV." These two "dominant modes," as they refer to them, are the Pacific Decadal Oscillation (PDO; Mantua *et al*., 1997) and the recently identified North Pacific Gyre Oscillation (NPGO; Di Lorenzo *et al*., 2008). The scholars emphasize that given the links between the PDO and the NPGO and global climate, the accurate characterization and the degree of predictability of these two modes in coupled climate models is an important "open question in climate dynamics."

Furtado *et al*. investigate this situation by comparing the output from the 24 coupled climate models used in the IPCC AR4 with observational analyses of sea level pressure (SLP) and sea surface temperature (SST), based on SLP data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis Project (Kistler *et al*., 2001), and SST data from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstruction SST dataset, version 3 (Smith *et al*., 2008), both of which data sets contain monthly mean values from 1950–2008 gridded onto a global 2.5° x 2.5° latitude-longitude grid for SLP and a 2° x 2° grid for SST.

The four U.S. scientists report model-derived "temporal and spatial statistics of the North Pacific Ocean modes exhibit significant discrepancies from observations in their twentieth-century climate, most visibly for the second mode, which has significantly more low-frequency power and higher variance than in observations." They also note the two dominant modes of North Pacific oceanic variability "do not exhibit significant changes in their spatial and temporal characteristics under greenhouse warming," stating "the ability of the models to capture the dynamics associated with the leading North Pacific oceanic modes, including their link to corresponding atmospheric forcing patterns and to tropical variability, is questionable."

There were even more "issues with the models," Furtado *et al*. note. "In contrast with observations," they report, "the atmospheric teleconnection excited by the El Niño-Southern Oscillation in the models does not project strongly on the AL [Aleutian low]-PDO coupled mode because of the displacement of the center of action of the AL in most models." In addition, they note, "most models fail to show the observational connection between El Niño Modoki-central Pacific warming and NPO [North Pacific Oscillation] variability in the North Pacific." They write, "the atmospheric teleconnections associated with El Niño Modoki in some models have a significant projection on, and excite the AL-PDO coupled mode instead."

Furtado *et al*. conclude "for implications on future climate change, the coupled climate models show no consensus on projected future changes in frequency of either the first or second leading pattern of North Pacific SST anomalies" and "the lack of a consensus in changes in either mode also affects confidence in projected changes in the overlying atmospheric circulation." In addition, they note the lack of consensus they found "mirrors parallel findings in changes in ENSO behavior conducted by van Oldenborgh *et al*. (2005), Guilyardi (2006) and Merryfield (2006)," and they state these significant issues "most certainly impact global climate change predictions."

Climate in the Southeast Pacific (SEP) near the coast of Peru and Chile, in the words of Zheng *et al*. (2011), "is controlled by complex upper-ocean, marine boundary layer and land processes and their interactions," and they say variations in this system have "significant impacts on global climate," citing Ma *et al*. (1996), Miller (1977), Gordon *et al*. (2000), and Xie (2004). However, they write, "it is well known that coupled atmosphere-ocean general circulation models tend to have systematic errors in the SEP region, including a warm bias in sea surface temperature and too little cloud cover," as demonstrated by Mechoso *et al*. (1995), Ma *et al*. (1996), Gordon *et al*. (2000), McAvaney *et al*. (2001), Kiehl and Gent (2004), Large and Danabasoglu (2006), Wittenberg *et al*. (2006), and Lin (2007). Even though these biases have what Zheng *et al.* call "important impacts" on the simulation of Earth's radiation budget and climate sensitivity, they note "it is still uncertain whether a similar bias is evident in most state-of-the-art coupled general circulation models [CGCMs] and to what extent the sea surface temperature [SST] biases are model dependent."

Using 20-year (1980–1999) model runs of the Climate of the Twentieth Century simulations of the 19 CGCMs that figured prominently in the (IPCC) *Fourth Assessment Report* (AR4), Zheng *et al*. examined systematic biases in SSTs under the stratus cloud deck in the SEP and upper-ocean processes relevant to those biases, attempting to isolate their causes.

The four U.S. researchers discovered "pronounced warm SST biases in a large portion of the southeast Pacific stratus region … in all models" and "negative biases in net surface heat fluxes … in most of the models." They found "biases in heat transport by Ekman currents largely contribute to warm SST biases both near the coast and the open ocean" and "in the coastal area, southwestward Ekman currents and upwelling in most models are much weaker than observed." "In the open ocean," they observed, "warm advection due to Ekman currents is overestimated." They write, "negative biases (cooling the ocean) in net surface heat flux" and "positive biases in shortwave radiation" are found in most models, because most models "do not generate sufficient stratus clouds" and "underestimate alongshore winds and coastal upwelling."

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1.3.7.3 Indian Ocean

Nagura *et al.* (2013) explain the term "Seychelles Dome" refers to the shallow climatological thermocline in the southwestern Indian Ocean, "where ocean wave dynamics efficiently affect sea surface temperature [SST], allowing SST anomalies to be predicted up to 1–2 years in advance." They also indicate this ability is significant: "The anomalous SSTs in the dome region subsequently impact various atmospheric phenomena, such as tropical cyclones (Xie *et al.,* 2002), the onset of the Indian summer monsoon (Joseph *et al.,* 1994; Annamalai *et al.,* 2005) and precipitation over India and Africa (Annamalai *et al.,* 2007; Izumo *et al*., 2008)."

They note "Yokoi *et al*. (2009) examined the outputs from models used in phase three of the Coupled Model Intercomparison Project (CMIP3) and found that many CMIP3 models have serious biases in this region." Hoping to find some improvement in the four years since Yokoi *et al.* conducted their research, Nagura *et al*. examined model biases associated with the Seychelles Dome using state-of-the-art ocean-atmosphere coupled general circulation models (CGCMs), "including those from phase five of the Coupled Model Intercomparison Project (CMIP5)."

Nagura *et al.* report several of the tested models "erroneously produce an upwelling dome in the eastern half of the basin, whereas the observed Seychelles Dome is located in the southwestern tropical Indian Ocean." They also note "the annual mean Ekman pumping velocity in these models is found to be almost zero in the southern off-equatorial region," which "is inconsistent with observations, in which Ekman upwelling acts as the main cause of the Seychelles Dome." Moreover, "in the models reproducing an eastward-displaced dome, easterly biases are prominent along the equator in boreal summer and fall, which result in shallow thermocline biases along the Java and Sumatra coasts via Kelvin wave dynamics and a spurious upwelling dome in the region." In a revealing final assessment of their findings, Nagura *et al*. conclude "compared to the CMIP3 models, the CMIP5 models are even worse in simulating the dome longitudes."

The Indian Ocean Dipole (IOD) is an irregular oscillation of sea-surface temperatures in which the western Indian Ocean becomes alternately warmer and then colder than the eastern part of the ocean. Cai and Cowan (2013) note "in most models, IOD peak-season amplitudes are systematically larger than that of the observed," and they say "understanding the cause of this bias is … essential for alleviating model errors and reducing uncertainty in climate projections."

The two Australian researchers analyzed sea surface temperatures (SSTs), thermocline characteristics (20°C isotherm depth), and zonal wind and precipitation outputs from 23 CMIP3 models and 33 CMIP5 models that attempted to simulate these climatic features over the last half of the twentieth century, after which they compared the model simulations with real-world observations. Cai and Cowan report "most models generate an overly deep western Indian Ocean thermocline that results in an unrealistic upward slope toward the eastern tropical Indian Ocean" and "the unrealistic thermocline structure is associated with too strong a mean easterly wind over the equatorial Indian Ocean, which is in turn supported by a slightly stronger mean west minus east SST gradient, reinforced by the unrealistic thermocline slope."

They conclude, "these biases/errors have persisted in several generations of models," such that "there is no clear improvement from CMIP3 to CMIP5."

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1.3.7.4 Equatorial/Tropical Regions

Wan *et al*. (2011) state "the notorious tropical bias problem in climate simulations of global coupled general circulation models (e.g., Mechoso *et al*., 1995; Latif *et al*., 2001; Davey *et al*., 2002; Meehl *et al*., 2005) manifests itself particularly strongly in the tropical Atlantic," and "while progress towards reducing tropical climate biases has been made in the tropical Pacific over the past decades (e.g., Deser *et al*., 2006), little or no progress has been made in the tropical Atlantic (Breugem *et al*., 2006; Richter and Xie, 2008; Wahl *et al*., 2009)." They write, "the climate bias problem is still so severe that one of the most basic features of the equatorial Atlantic Ocean—the eastward shoaling thermocline—cannot be reproduced by most of the Intergovernmental Panel on Climate Change (IPCC) assessment report (AR4) models," citing Richter and Xie (2008).

In their own investigation of the subject, Wan *et al*. "show that the bias in the eastern equatorial Atlantic has a major effect on sea-surface temperature (SST) response to a rapid change in the Atlantic Meridional Overturning Circulation (AMOC)." They do so by exemplifying the problem "through an inter-model comparison study of tropical Atlantic response to an abrupt change in [the] AMOC using the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Climate Model (CM2.1) and the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3)" and dissecting the oceanic mechanisms responsible for the difference in the models' SST responses.

Their analysis demonstrates the different SST responses of the two models are "plausibly attributed to systematic differences in the simulated tropical Atlantic ocean circulation." The ultimate implication of Wan *et al*.'s findings is, in their words, that "in order to accurately simulate past abrupt climate changes and project future changes, the bias in climate models must be reduced."

Shin and Sardeshmukh (2011) note there is "increased interest in the ability of climate models to simulate and predict surface temperature and precipitation changes on sub-continental scales," and they state these regional trend patterns "have been strongly influenced by the warming pattern of the tropical oceans," which suggests correctly simulating the warming pattern of the tropical oceans is a prerequisite for correctly simulating sub-continental-scale warming patterns.

In exploring this subject further, Shin and Sardeshmukh compared multi-model ensemble simulations of the last half-century with corresponding observations, focusing on the world's tropical oceans, as well as the land masses surrounding the North Atlantic Ocean, including North America, Greenland, Europe, and North Africa. This was done, as they describe it, using "all available coupled [atmosphere-ocean] model simulations of the period 1951–1999 from 18 international modeling centers, generated as part of the IPCC's 20th century climate simulations with prescribed time-varying radiative forcings associated with greenhouse gases, aerosols, and solar variations."

The two researchers report "the tropical oceanic warming pattern is poorly represented in the coupled simulations," and they state their analysis "points to model error rather than unpredictable climate noise as a major cause of this discrepancy with respect to the observed trends." They found "the patterns of recent climate trends over North America, Greenland, Europe, and North Africa are generally not well captured by state-of-the-art coupled atmosphere-ocean models with prescribed observed radiative forcing changes."

Commenting on their work, Shin and Sardeshmukh write, "the fact that even with full atmosphere-ocean coupling, climate models with prescribed observed radiative forcing changes do not capture the pattern of the observed tropical oceanic warming suggests that either the radiatively forced component of this warming pattern was sufficiently small in recent decades to be dwarfed by natural tropical SST variability, or that the coupled models are misrepresenting some important tropical physics." Since the greenhouse-gas forcing of climate "in recent decades" is claimed by the IPCC to have been unprecedented over the past millennium or more, it would appear the models are indeed "misrepresenting some important tropical physics."

Li and Xie (2012) write, "state-of-the-art coupled ocean-atmosphere general circulation models (CGCMs) suffer from large errors in simulating tropical climate, limiting their utility in climate prediction and projection." Describing the size of the several errors, they say they "are comparable or larger in magnitude than observed interannual variability and projected change in the 21st century."

The two researchers say the "well-known errors" include "too weak a zonal SST gradient along the equatorial Atlantic," citing Davey *et al*. (2002) and Richter and Xie (2008); "an equatorial cold tongue that penetrates too far westward in the Pacific," citing Mechoso *et al*. (1995) and de Szoeke and Xie (2008); and "too warm SSTs over the tropical Southeast Pacific and Atlantic, and a spurious double intertropical convergence zone," citing Lin (2007). They point out "these errors have persisted in several generations of models for more than a decade."

Closer inspection of zonal SST profiles along the equator is found by Li and Xie to reveal "basin-wide offsets, most obvious in the Indian (Saji *et al*., 2006) but visible in the Pacific (de Szoeke and Xie, 2008), and Atlantic (Richter and Xie, 2008) Oceans." They add "it is unclear whether such basin-wide offset errors are limited to individual tropical basins or shared among all the basins."

Li and Xie then "examine the Climate of the Twentieth Century (20C3M) simulations (also termed as 'historical' runs) from 22 CMIP3 and 21 CMIP5 CGCMs for a 30-year period of 1970–99, together with their available Atmospheric Model Intercomparison Project (AMIP) runs that are forced with the observed SST." They find two types of tropical-wide offset biases. One of them "reflects the tropical mean SST differences from observations and among models, with a broad meridional structure and of the same sign across all basins of up to 2°C in magnitude," while the other "is linked to inter-model variability in the cold tongue temperatures in the equatorial Pacific and Atlantic."

In further describing their findings, the two researchers write "the first-type offset error is ascribed to atmospheric model representation of cloud cover, with cloudy models biasing low in tropical-wide SST," while "the second type originates from the diversity among models in representing the thermocline depth, with deep thermocline models biasing warm in the equatorial cold tongues."

Also addressing the ability of CGCMs to accurately model the equatorial and tropical regions, Zheng *et al*. (2012) note "the equatorial Pacific is observed to have a minimum sea surface temperature (SST) that extends from the west coasts of the Americas into the central Pacific," and this "extension of cool water is commonly referred to as the cold tongue (Wyrtki, 1981)." They state "it is generally argued that the Pacific cold tongue is maintained by horizontal advection of cold water from the east and by upwelling of cold water from the subsurface." The three researchers proceed to examine "the contribution of ocean dynamics to sea surface temperature biases in the eastern Pacific cold tongue region in fifteen coupled general circulation models (CGCMs) participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4)," analyzing "twenty years (1980–1999) of the twentieth-century climate simulations from each model."

Zheng *et al.* find "errors in both net surface heat flux and total upper ocean heat advection significantly contribute to the excessive cold tongue in the equatorial Pacific" and conclude "the stronger heat advection in the models is caused by overly strong horizontal heat advection associated with too strong zonal currents, and overly strong vertical heat advection due to excessive upwelling and the vertical gradient of temperature." They note "the Bjerknes feedback in the coupled models is shown to be weaker than in observations, which may be related to the insufficient response of surface zonal winds to SST in the models and an erroneous subsurface temperature structure," such that "the cold tongue becomes colder than the cold tongue in the observations." Zheng *et al*. conclude "more work is needed on the role of the ocean model and ocean-atmosphere feedback in the growth of the double-ITCZ pattern."

In looking at equatorial SSTs, Vanniere *et al*. (2013) state "the cold equatorial SST bias in the tropical Pacific that is persistent in many coupled OAGCMs [Ocean-Atmosphere Global Climate Models] severely impacts the fidelity of the simulated climate and variability in this key region, such as the ENSO [El Niño-Southern Oscillation] phenomenon." More specifically, they note "the seasonal equatorial cold tongue extends too far west, is too cold in the east Pacific and is associated with too strong trade winds," citing Davey *et al*. (2001), AchutaRao and Sperber (2006), and Lin (2007). In addition, they write, "a warm SST bias is observed near the coast of South America," which is "associated with a lack of low clouds and deficient winds." And they note "mean state biases relevant to ENSO also include too strong easterlies in the west Pacific and the double ITCZ [Intertropical Convergence Zone] syndrome," citing Lin (2007) and de Szoeke and Xie (2008).

In attempting to unscramble and resolve these many problems, Vanniere *et al*. (2013) used seasonal re-forecasts or hindcasts to "track back" the origin of the major cold bias, so that "a time sequence of processes involved in the advent of the final mean state errors can then be proposed," applying this strategy to the ENSEMBLES-FP6 project multi-model hindcasts of the last decades. The researchers discovered "the models are able to reproduce either El Niño or La Niña close to observations, but not both." Therefore, they conclude, "more work is needed to understand the origin of the zonal wind bias in models," and, in this regard, "understanding the dynamical and thermodynamical mechanisms that drive the tropical atmosphere is required both to alleviate OAGCM errors and to describe the full extent of the atmosphere's role in tropical variability, such as ENSO."

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1.3.7.5 Southern Ocean

Weijer *et al*. (2012) note "the Southern Ocean is a region of extremes: it is exposed to the most severe winds on the Earth (Wunsch, 1998), the largest ice shelves (Scambos *et al*., 2007), and the most extensive seasonal sea ice cover (Thomas and Dieckmann, 2003)." They indicate various interactions among the atmosphere, ocean, and cryosphere in this region "greatly influence the dynamics of the entire climate system through the formation of water masses and the sequestration of heat, freshwater, carbon, and other properties (Rintoul *et al*., 2001)."

Against this backdrop, Weijer *et al*. "explored several key aspects of the Southern Ocean and its climate in the new Community Climate System Model, version 4 (CCSM4)," including "the surface climatology and inter-annual variability, simulation of key climate water masses (Antarctic Bottom Water [AABW], Subantarctic Mode Water [SAMW], and Antarctic Intermediate Water [AAIW]), the transport and structure of the Antarctic Circumpolar Current [ACC], and inter-basin exchange via the Agulhas and Tasman leakages and at the Brazil-Malvinas Confluence [BMC]."

The nine researchers find "the CCSM4 has varying degrees of accuracy in the simulation of the climate of the Southern Ocean when compared with observations." Results of this comparison include: (1) "the seasonally ice-covered regions are mildly colder (ΔSST > -2°C) than observations," (2) "sea ice extent is significantly larger than observed," (3) "north of the seasonal ice edge, there is a strong (-4°C < ΔSST < -1°C) cold bias in the entire Pacific sector south of 50°S and in the western Australian-Antarctic Basin," (4) "positive biases (1° < ΔSST < 4°C) are found in the Indian and Atlantic sectors of the Southern Ocean," (5) "significant differences are found in the Indian and Pacific sectors north of the ACC, with the CCSM4 model being too cold (< -2°C) and fresh (<-0.3 psu)," (6) "AABW adjacent to the Antarctic continent is too dense," (7) "North Atlantic Deep Water is too salty (>0.2 psu)," (8) "in the Indian and Pacific sectors of the Southern Ocean, north of 50°S and below 3000 meters, the too-salty AABW penetrates northward, resulting in a denser-than-observed abyssal ocean in CCSM4," (9) "the model underestimates the depth of the deep winter mixed layers in the Indian and eastern Pacific sectors of the Southern Ocean north of the ACC," (10) "in the southern Tasman Sea and along the eastern Indian Ocean boundary ... the model mixed layer depth is deeper than observed by more than 400 meters," (11) "in all sectors of the Southern Ocean, Model CFC-11 concentrations in the lower thermocline and intermediate waters are lower than observed," (12) "model CFC-11 concentrations in the deep ocean (below 2000 meters) are lower than observed in the basins adjacent to the Antarctic continent," (13) "model surface CFC-11 concentrations are higher than observed," (14) "the production of overflow waters in the Ross Sea is too low by about a factor of 2 relative to the limited observations," (15) "the depth at which the product water settles was also shown to be too shallow by about a factor of 2," (16) "the subtropical gyre of the South Atlantic is too strong by almost a factor of 2, associated with a strong bias in the wind stress," (17) the mean position of the BMC is too far south in the CCSM4," and (18) "the model variability in the position of the BMC is significantly less than observations."

Weijer *et al*. conclude that as the CCSM4 currently stands, it "may underestimate the sequestration of heat, carbon, and other properties to the interior ocean," such that its parameterizations may "lead to significant biases in the representation of the Southern Ocean and its climate."

According to Sallee *et al*. (2013), "the Southern Ocean is the dominant anthropogenic carbon sink of the world's oceans and plays a central role in the redistribution of physical and biogeochemical properties around the globe," citing Sarmiento *et al*. (2004). They add "one of the most pressing issues in oceanography is to understand the rate, the structure and the controls of the water mass overturning circulation in the Southern Ocean and to accurately represent these aspects in climate models." Focusing on five water masses crucial for the Southern Ocean overturning circulation—surface subTropical Water (TW), Mode Water (MW), Intermediate Water (IW), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (AABW)—Sallee *et al*. studied the ability of 21 of the CMIP5 models to simulate what they describe as the most basic properties of each of these water masses: temperature, salinity, volume, and outcrop area.

The authors describe several important findings. They note, "the water masses of the Southern Ocean in the CMIP5 models are too warm and light over the entire water column," with the largest biases being found in the ventilated layers, and "the mode water layer is poorly represented in the models and both mode and intermediate water have a significant fresh bias." They further find, "in contrast to observations (e.g., Rintoul, 2007), bottom water is simulated to become slightly saltier" and "when compared to observation-based reconstructions," the models "exhibit a slightly larger rate of overturning at shallow to intermediate depths, and a slower rate of overturning deeper in the water column." Given such discrepancies, the seven scientists conclude "many of the biases and future changes identified in this study are expected to have significant impacts on the marine carbon cycle." These biases and the changes they spawn are not trivial and must be corrected before they are used to forecast the future of the overturning circulation of the Southern Ocean and its impact on global climate.

Heuze *et al.* (2013) point out "the ability of a model to adequately depict bottom water formation is crucial for accurate prediction of changes in the thermohaline circulation," citing Hay (1993). They note, however, "this process is particularly challenging to represent in the current generation of climate models" and "the last generation of models in CMIP3 poorly represented Southern Ocean transport and heat fluxes," citing Russell *et al.* (2006).

Heuze *et al*. assessed "Southern Ocean potential temperature, salinity, density and sea ice concentration in fifteen CMIP5 historical simulations (means of the twenty August monthly mean fields from 1986 to 2005)," comparing the 20-year mean model fields with historical hydrographic data and Hadley Centre sea ice climatologies. They note no model reproduces the process of Antarctic bottom water formation accurately, for "instead of forming dense water on the continental shelf and allowing it to spill off," the models "present extensive areas of deep convection, thus leading to an unrealistic unstratified open ocean."

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1.3.7.6 Sea Ice

Writing about how well the models of more than a decade ago simulated changes in sea ice, Holland (2001) states "the present situation with respect to the state-of-the-art global climate models is that some physical processes are absent from the models and, with the rather coarse-resolution grids used, some physical processes are ill resolved ... and therefore in practical terms missing from the simulations." Holland thus questions "whether the simulations obtained from such models are in fact physically meaningful" and conducted an analysis to determine the difference in model evolution of sea ice cover using a relatively coarse-resolution grid versus a fine-resolution grid, with specific emphasis on the presence and treatment of a mesoscale ocean eddy and its influence on sea ice cover.

Resolving the ocean eddy field using the fine-resolution model was found to have a measurable impact on sea ice concentration, implying a "fine-resolution grid may have a more efficient atmosphere-sea ice-ocean thermodynamic exchange than a coarse one." Holland concludes his study demonstrated "yet again that coarse-resolution coupled climate models are not reaching fine enough resolution in the polar regions of the world ocean to claim that their numerical solutions have reached convergence."

Two years later, the situation had not improved much. Laxon *et al*. (2003) used an eight-year time series (1993–2001) of Arctic sea-ice thickness derived from measurements of ice freeboard made by 13.8-GHz radar altimeters carried aboard ERS-1 and 2 satellites to determine the mean thickness and variability of Arctic sea ice between latitudes 65 and 81.5°N, a region covering the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. Mean winter sea-ice thickness over the region was found to be 2.73 meters with a standard deviation of ± 9% of the average, a variability 50 percent greater than predicted by climate models "and probably more," the authors state. They report their analysis "excludes variability that occurs over timescales of longer than a decade."

Further comparing their observations with model projections, the authors noted several discrepancies. First, Laxon *et al*. specifically note their observations "show an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models," clearly indicating the models do not reproduce reality very well in this regard. Second, they state "the interannual variability in thickness [9%] compares with a variability in mean annual ice extent of 1.7% during the same period," which, in the words of the authors, "undermines the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent." Third, concerning the origin of Arctic sea-ice thickness variability, the authors discovered "a significant (R^2 = 0.924) correlation between the change in the altimeter-derived thickness between consecutive winters, and the melt season length during the intervening summer." This "observed dominant control of summer melt on the interannual variability of mean ice thickness," according to the researchers, "is in sharp contrast with the majority of models, which suggest that ice thickness variability in the Arctic Ocean is controlled mainly by wind and ocean forcing." Fourth, the authors' data demonstrate "sea ice mass can change by up to 16% within one year," which "contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming," representing still another failure of the models.

Laxon *et al*. close their analysis by stating their results "show that errors are present in current simulations of Arctic sea ice," concluding, "until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and future, changes in Arctic ice cover will be open to question."

Eisenman *et al*. (2007) used two standard thermodynamic models of sea ice to calculate equilibrium Arctic ice thickness based on simulated Arctic cloud cover derived from 16 different global climate models evaluated for the IPCC's *Fourth Assessment Report*. Results indicate there was a 40 Wm^{-2} spread among the models in terms of their calculated downward longwave radiation, for which both sea ice models calculated an equilibrium ice thickness ranging from one to more than ten meters.

They note the mean 1980–1999 Arctic sea ice thickness simulated by the 16 GCMs ranged from only 1.0 to 3.9 meters, a far smaller inter-model spread. Hence, they say they were "forced to ask how the GCM simulations produce such similar present-day ice conditions in spite of the differences in simulated downward longwave radiative fluxes?"

The three researchers say "a frequently used approach" to resolving this problem "is to tune the parameters associated with the ice surface albedo" to get a more realistic answer. "In other words," as they continue, "errors in parameter values are being introduced to the GCM sea ice components to compensate simulation errors in the atmospheric components." They conclude "the thinning of Arctic sea ice over the past half-century can be explained by minuscule changes of the radiative forcing that cannot be detected by current observing systems and require only exceedingly small adjustments of the model-generated radiation fields" and, therefore, "the results of current GCMs cannot be relied upon at face value for credible predictions of future Arctic sea ice."

Kwok (2011) notes near the midpoint of the last decade, simulations of Arctic Ocean sea ice characteristics produced by the climate models included in the World Climate Research Programme's Coupled Model Intercomparison Project phase *3* (CMIP3) were far from what might have been hoped. Specifically, he writes "Zhang and Walsh (2006) note that even though the CMIP3 models capture the negative trend in sea ice area, the inter-model scatter is large," "Stroeve *et al*. (2007) show that few models exhibit negative trends that are comparable to observations" and "Eisenman *et al*. (2007) conclude that the results of current CMIP3 models cannot be relied upon for credible projections of sea ice behavior."

In his more recent analysis of the subject, based on the multi-model data set of Meehl *et al*. (2007), Kwok, a researcher at the Jet Propulsion Laboratory, compares CMIP3 model simulations "with observations of sea ice motion, export, extent, and thickness and analyzes fields of sea level pressure and geostrophic wind of the Arctic Ocean." Kwok's analysis demonstrated "the skill of the CMIP3 models (as a group) in simulation of observed Arctic sea ice motion, Fram Strait export, extent, and thickness between 1979 and 2008 seems rather poor." He notes "model-data differences and inter-model scatter of the sea ice parameters in the summarizing statistics are high" and "the spatial pattern of Arctic sea ice thickness, a large-scale slowly varying climatic feature of the ice cover, is not reproduced in a majority of the models." Consequently, he writes, "the models will not get the main features of natural sea ice variability that may be dominating recent sea ice extent declines as well as the long-term greenhouse response."

"Because the model simulations have difficulties reproducing the mean patterns of Arctic circulation and thickness," Kwok concludes, his analysis suggests there are "considerable uncertainties in the projected rates of sea ice decline even though the CMIP3 data set agrees that increased greenhouse gas concentrations will result in a reduction of Arctic sea ice area and volume."

The most recent investigation into the topic was conducted by Turner *et al*. (2013). The authors state "Phase 5 of CMIP (CMIP5) will provide the model output that will form the basis of the *Fifth Assessment Report* (AR5) of the IPCC," and they therefore thought it important to determine how well these models represent reality. They set out to examine "the annual cycle and trends in Antarctic sea ice extent (SIE) for 18 models used in phase 5 of the Coupled Model Intercomparison Project that were run with historical forcing for the 1850s to 2005."

According to the five researchers, their examination indicated "the majority of models have too small of an SIE at the minimum in February" and "several of the models have less than two-thirds of the observed SIE at the September maximum. They further note, "in contrast to the satellite data, which exhibit a slight increase in SIE, the mean SIE of the models over 1979–2005 shows a decrease in each month"; "the models have very large differences in SIE over 1860–2005"; and "the negative SIE trends in most of the model runs over 1979–2005 are a continuation of an earlier decline, suggesting that the processes responsible for the observed increase over the last 30 years are not being simulated correctly."

Turner *et al*. conclude "many of the SIE biases in the CMIP3 runs remain in CMIP5." More particularly, for example, they state, "as with CMIP3, the models do not simulate the recent increase in Antarctic SIE observed in the satellite data."

Confirming the results of Turner *et al*. (2013), Swart and Fyfe (2013) examined the consistency between satellite observations and CMIP5 climate model projections of the evolution of Antarctic sea ice extent. They note, "The CMIP5 multimodel ensemble mean shows a large negative trend in annual mean sea ice area of -3.0×10^{11} m^2/decade over the historical period" and "By contrast, the observations show a statistically significant positive trend of 1.39 ± 0.82 x 10^{11} m^2/decade (95% confidence interval accounting for serial correlation).” (See Figure 1.3.7.6.1.)

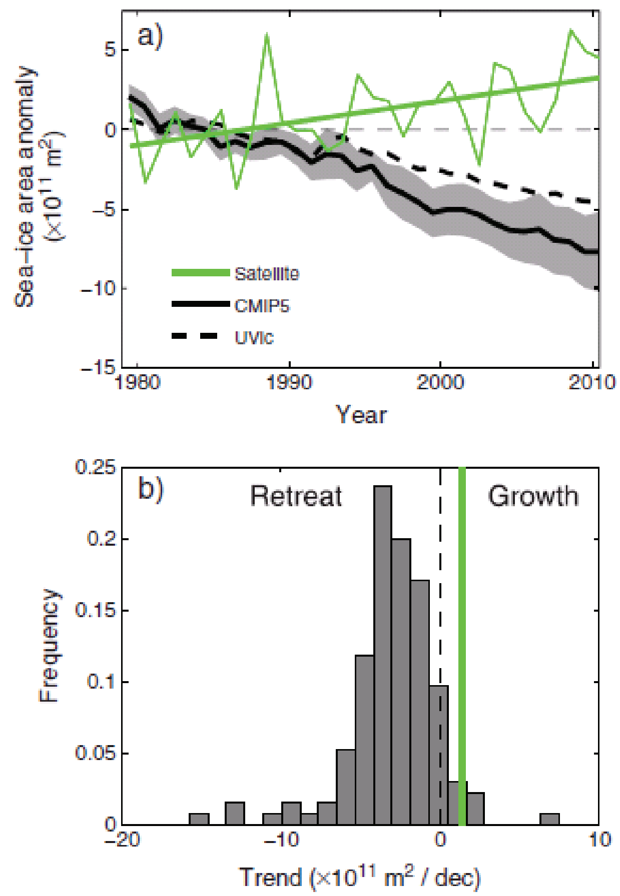

Figure 1.3.7.6.1. (a) Annual mean Antarctic sea ice area anomaly relative to the 1979–1989 base period, for satellite observations using the NASATEAM algorithm, the ensemble mean of 38 CMIP5 models (with a total of 135 realizations, listed in the supporting information), with the envelope indicating the 95% confidence interval, and the University of Victoria (UVic) model. The thick green curve is the linear least squares fit to the observed anomalies. (b) Distribution of linear trends in annual mean sea ice area for the CMIP5 models and the observed trend. Adapted from Figure 1 of Swart, N.C. and Fyfe, J.C., 2013. The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. *Geophysical Research Letters* **40**: 10.1002/grl.50820.

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1.3.8 Soil Moisture

Climate models have long indicated that CO_2-induced global warming will increase evapotranspiration, causing decreases in soil moisture content that may offset modest increases in continental precipitation and lead to greater aridity in both water-limited natural ecosystems and lands devoted to agriculture (Manabe and Wetherald, 1986; Rind, 1988; Gleick, 1989; Vlades *et al*., 1994; Gregory *et al*., 1997; Komescu *et al*., 1998). This section examines pertinent scientific literature to assess this claim.

In a turn-of-the century evaluation of how climate modelers had progressed in their efforts to improve their simulations of soil moisture content over the prior few years, Srinivasan *et al*. (2000)

examined "the impacts of model revisions, particularly the land surface representations, on soil moisture simulations, by comparing the simulations to actual soil moisture observations." They write, "the revised models do not show any systematic improvement in their ability to simulate observed seasonal variations of soil moisture over the regions studied." They also note, "there are no indications of conceptually more realistic land surface representations producing better soil moisture simulations in the revised climate models." They report a "tendency toward unrealistic summer drying in several models," which they note was "particularly relevant in view of the summer desiccation projected by GCMs considered in future assessments of climate change."

Although Srinivasan *et al*. report "simpler land-surface parameterization schemes are being replaced by conceptually realistic treatments," as the climate modeling enterprise evolves, they note "improvements gained by such changes are ... not very apparent."

A similar assessment was supplied that year by Robock *et al*. (2000), who developed a massive collection of soil moisture data for more than 600 stations from a wide variety of climatic regimes found within the former Soviet Union, China, Mongolia, India, and the United States. In describing these data sets they also state an important ground rule. Sometimes, they note, "the word 'data' is used to describe output from theoretical model calculations, or values derived from theoretical analysis of radiances from remote sensing." However, they state, "we prefer to reserve this word for actual physical observations," noting "all the data in our data bank are actual *in situ* observations."

This distinction is important, for one of the illuminating analyses Robock *et al*. performed with their data was to check summer soil moisture trends simulated by the Geophysical Fluid Dynamics Laboratory's general circulation model of the atmosphere as forced by transient CO_2 and tropospheric sulfate aerosols for specific periods and regions for which they had actual soil moisture data. They found, "although this model predicts summer desiccation in the next century, it does not in general reproduce the observed upward trends in soil moisture very well," a mammoth understatement considering the predictions and observations go in opposite directions. As noted elsewhere in their paper, "in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen."

Another important report on the subject is presented five years later, again by Robock *et al*. (2005), who note "most global climate model simulations of the future, when forced with increasing greenhouse gases and anthropogenic aerosols, predict summer desiccation in the midlatitudes of the Northern Hemisphere (e.g., Gregory *et al*., 1997; Wetherald and Manabe, 1999; Cubasch *et al*., 2001)," adding "this predicted soil moisture reduction, the product of increased evaporative demand with higher temperatures overwhelming any increased precipitation, is one of the gravest threats of global warming, potentially having large impacts on our food supply."

With the explicit intent "to evaluate these model simulations," the three American and two Ukrainian scientists present "the longest data set of observed soil moisture available in the world, 45 years of gravimetrically-observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April-October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958-2002." As they describe it, "the observations show a positive soil moisture trend for the entire period of observation, with the trend leveling off in the last two decades," noting "even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals."

In light of these real-world observations, Robock *et al*. note "although models of global warming predict summer desiccation in a greenhouse-warmed world, there is no evidence for this in the observations yet, even though the region has been warming for the entire period." In attempting to explain this dichotomy, they state the real-world increase in soil moisture content may have been driven by a downward trend in evaporation caused by the controversial "global dimming" hypothesis (Liepert *et al*., 2004). Alternatively, we offer it may have been driven by the well-known anti-transpirant effect of atmospheric CO_2 enrichment, which tends to conserve water in the soils beneath crops and thereby leads to enhanced soil moisture contents, as has been demonstrated in a host of experiments conducted in real-world field situations.

One especially outstanding study in this regard is that of Zaveleta *et al*. (2003), who tested the hypothesis that soil moisture contents may decline in a CO_2-enriched and warmer world, in a two-year study of an annual-dominated California grassland at the Jasper Ridge Biological Preserve, Stanford, California, USA, where they delivered extra heating to a number of free-air CO_2 enrichment (FACE) plots (enriched with an extra 300 ppm of CO_2) via IR heat lamps suspended over the plots that warmed the surface of the soil beneath them by 0.8-1.0°C.

The individual effects of atmospheric CO_2 enrichment and soil warming were of similar magnitude, and acting together they enhanced mean spring soil moisture content by about 15 percent over that of the control treatment. The effect of CO_2 was produced primarily as a consequence of its ability to cause partial stomatal closure and thereby reduce season-long plant water loss via transpiration. In the case of warming, there was an acceleration of canopy senescence that further increased soil moisture by reducing the period of time over which transpiration losses occur, all without any decrease in total plant production.

Zaveleta *et al*. note their findings "illustrate the potential for organism-environment interactions to modify the direction as well as the magnitude of global change effects on ecosystem functioning." Whereas model projections suggest vast reaches of agricultural land will dry up and be lost to profitable production in a CO_2-enriched world of the future, this study suggests just the opposite could occur. As the six researchers describe it, "we suggest that in at least some ecosystems, declines in plant transpiration mediated by changes in phenology can offset direct increases in evaporative water losses under future warming."

Guo and Dirmeyer (2006) compared soil moisture simulations made by 11 models in the Second Global Soil Wetness Project, a multi-institutional modeling research activity intended to produce a complete multi-model set of land surface state variables and fluxes by using land surface models driven by the 10-year period of data provided by the International Satellite Land Surface Climatology Project Initiative II, against real-world observations made on the top meter of grassland and agricultural soils located within parts of the former Soviet Union, the United States (Illinois), China, and Mongolia that are archived in the Global Soil Moisture Data Bank.

According to the authors, "simulating the actual values of observed soil moisture is still a challenging task for all models," as they note "both the root mean square of errors (RMSE) and the spread of RMSE across models are large" and "the absolute values of soil moisture are poorly simulated by most models." In addition, they report "within regions there can be tremendous variations of any model to simulate the time series of soil moisture at different stations."

Guo and Dirmeyer suggest the errors and variations are serious problems for the models. First, the two researchers write "the land surface plays a vital role in the global climate system through interactions with the atmosphere."They also note "accurate simulation of land surface states is critical to the skill of weather and climate forecasts" and soil moisture "is the definitive land surface state variable; key for model initial conditions from which the global weather and climate forecasts begin integrations, and a vital factor affecting surface heat fluxes and land surface temperature."

Li *et al*. (2007) compared soil moisture simulations derived from the IPCC's AR4 climate models, which were driven by observed climate forcings, for the period 1958–1999 with actual measurements of soil moisture made at more than 140 stations or districts in the mid-latitudes of the Northern Hemisphere. The latter were averaged in such a way as to yield six regional results: one each for the Ukraine, Russia, Mongolia, Northern China, Central China, and Illinois (USA). According to the three researchers, the models showed realistic seasonal cycles for the Ukraine, Russia, and Illinois but "generally poor seasonal cycles for Mongolia and China." In addition, they report the Ukraine and Russia experienced soil moisture increases in summer "that were larger than most trends in the model simulations." The researchers found "only two out of 25 model realizations show trends comparable to those observations," and the two realistic model-derived trends were "due to internal model variability rather than a result of external forcing," which means the two reasonable matches were in fact accidental.

Noting further "changes in precipitation and temperature cannot fully explain soil moisture increases for [the] Ukraine and Russia," Li *et al*. write, "other factors might have played a dominant role on the observed patterns for soil moisture." They mention solar dimming, plus the fact that in response to elevated atmospheric CO_2 concentrations, "many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere," so "more water is likely to be stored in the soil or [diverted to] runoff," reporting this phenomenon was detected in continental river runoff data by Gedney *et al*. (2006).

Publishing in *Geophysical Research Letters*, Christensen and Boberg (2012) compared monthly mean temperatures projected by 34 global climate models included in phase 5 of the Coupled Model Intercomparison Project (CMIP5) with observations from the University of East Anglia's Climatic Research Unit for 26 different regions covering all major land areas of the world for the period 1961–2000, for which they employed quantile-quantile (q-q) diagrams. This revealed the existence of "a warm period positive temperature dependent bias" for "many of the models with many of the chosen climate regions"; the magnitude of this temperature dependence varied considerably among the models.

Analyzing the role of this difference as "a contributing factor for some models to project stronger regional warming than others," the two scientists found "models with a positive temperature dependent bias tend to have a large projected temperature change" and "these tendencies increase with increasing global warming level." In addition, they state this situation "appears to be linked with the ability of models to capture complex feedbacks accurately," noting in particular that land-surface/atmosphere interactions are treated differently and with different degrees of realism among the various models they investigated and "soil moisture-temperature feedbacks are relevant for temperature extremes in a large fraction of the globe."

Christensen and Boberg conclude, "accepting model spread as a way to portray uncertainty of the projection estimate may result in an overestimation of the projected warming and at the same time indicate little model agreement on the mean value." They note "a non-negligible part" of this overestimation "is due to model deficiencies" that have yet to be overcome.

In light of the observations discussed above, it would appear almost all climate models employed to date have greatly erred with respect to what Robock *et al*. (2005) describe as "one of the gravest threats of global warming"—soil moisture content. Not only has the model-predicted decline in Northern Hemispheric midlatitude soil moisture contents failed to materialize under the combined influence of many decades of rising atmospheric CO_2 concentrations and temperatures, it has become less of a threat, possibly as a consequence of biological impacts of the ongoing rise in the air's CO_2 content.

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1.3.9 Biological Processes

In a landmark paper published in *Global Change Biology*, Eastman *et al*. (2001) described the first comprehensive study of CO_2-induced regional climate change based on a hybrid atmosphere/vegetation model composed of linked meteorological and plant growth sub-models.

The authors of the groundbreaking study began by citing a number of peer-reviewed scientific research papers that demonstrated the likelihood of what they called "a crucial role for biospheric feedbacks on climate," including processes driven by CO_2-induced changes in land surface albedo, leaf stomatal conductance, plant rooting profile, fractional coverage of the land by vegetation, plant roughness length and displacement height, vegetation phenology, time of planting and harvesting (in the case of agricultural crops), and plant growth. Next, they validated the model against real-world meteorological and plant growth data obtained for the 1989 growing season for the area located between approximately 35° and 48° N latitude and 96° and 110° W longitude. Last, they investigated how the climate of the region changes when (1) only the radiative effects of a doubling of the air's CO_2 concentration are considered, (2) only the biological effects of a doubling of the air's CO_2 concentration are considered, and (3) the radiative and biological effects of a doubling of the air's CO_2 concentration occur simultaneously.

With respect to the area-averaged and seasonally averaged daily maximum air temperature, the radiative effects of a doubling of the atmospheric CO_2 concentration lead to a warming of only 0.014°C, and the biological effects of the extra CO_2 produced a cooling of fully 0.747°C. Considered together and including a nonlinear interaction term, the simultaneous radiative and biological effects of a doubling of the air's CO_2 content thus produced a net cooling of 0.715°C.

With respect to the area-averaged and seasonally averaged daily minimum air temperature, the radiative effects of a doubling of the atmospheric CO_2 concentration led to a warming of 0.097°C, while the biological effects of the extra CO_2 produced a warming of 0.261°C. Considered together and again including the nonlinear interaction term, the simultaneous radiative and biological effects of a doubling of the air's CO_2 content thus produced a net warming of 0.354°C.

During the day, then, when high air temperatures can be detrimental to both plant and animal life, the combined effect of the simultaneous radiative and biological impacts of an increase in the air's CO_2 content acts to decrease daily maximum air temperature, alleviating potential heat stress. During the night, when low temperatures can be detrimental to plant and animal life, the combined effect of the radiative and biological impacts of an increase in the air's CO_2 content acts to increase daily minimum air temperature, alleviating potential cold stress. When considering the day and night air temperature changes together, the mean daily air temperature range is reduced by approximately 1.069°C, leading to a more thermally stable environment, which in this case was also about 0.180°C cooler in the mean.

The authors also found the CO_2-induced change in area-averaged and seasonally averaged leaf area index was increased (+21.8%) with the simultaneous expression of the radiative and biological effects of a doubling of the air's CO_2 content.

In summarizing their findings, the authors report "it is clear" the radiative effects of a doubling of the air's CO_2 content have "little effect on anything" and play but a "minor role in the coupled biological and atmospheric system." The authors acknowledge their analysis is "a regional-scale sensitivity study," the results of which "cannot be linearly scaled up to global scales."

Nevertheless the authors follow that caveat by noting their results "suggest that the regional response could be on the order of global climate sensitivities."

Thus they conclude, "climate change that results from anthropogenic increases of CO_2 must consider the biological effects of enriched CO_2 as well as its radiative effect." Most models exclude this important interaction.

In a paper published a decade later, Delire *et al.* (2011) used the CCMv3 and LMDz atmospheric GCMs and coupled these models to the latest versions of the Integrated Biosphere Simulator (IBIS) (Foley *et al*. 1996) and the ORCHIDEE biosphere model (Krinner *et al*. 2005), respectively. Each is a land surface model that includes plant characteristics such as the physiology of plant cover, plant phenology, carbon cycling, plant type competition, photosynthesis, and respiration. Both include daily and annual vegetation cycles and distinguish between trees and other types of vegetation (grasses, shrubs). Delire *et al.* ran each model with full capabilities and then by keeping the vegetation constant (fixed).

The GCM modeling strategy used by Delire *et al*. was to simulate the climate using observed sea surface temperatures from 1870–1899 available from the Hadley Centre in England. Their goal was to remove the impact of the ocean in order to highlight land-surface process differences in the coupled systems. The model was run for 400 years; the last 300 were used for analysis.

The interannual variability in plant cover generated by both models was similar to that of observed plant cover variability derived using satellite observations for 1982–1994. The LMDz-ORCHIDEE model showed stronger interannual variability, but in both the variability in tree cover was less than 5 percent, whereas for grasses it could be as much as 10 to 20 percent. Vegetation affected climate, as inferred by comparing the dynamic to fixed vegetation. The model strategy precluded comparison with observed climate.

The dynamic vegetation runs showed stronger low frequency variability than the fixed runs for both temperature and precipitation for each model system, but the disparity between the fixed and dynamic run was stronger for the CCMv3-IBIS system (Figure 1.3.9.1). The strength of the variability (0.05-2.0°C) compared favorably to that inferred by previous studies. The feedback between temperature and plant growth was generally positive (warmer temperatures, increased vegetation) in the mid-latitudes and poleward. The feedback was generally negative and weaker in semi-arid regions (increased vegetation, more evaporation, cooler temperatures). There was only a weak positive feedback in the precipitation over most areas of the globe.

As we begin to understand more about the climate system, including the complexity of heat and mass exchange between various portions of it, we can more effectively model the past climate, including its variability. However, many of the climate simulations used to project future climate are fairly simple models that do not include a dynamic ocean or realistic representations of biological processes on land. These are problems that cannot continue to be ignored or overlooked. As Delire *et al*. indicate, "terrestrial ecosystems provide 'memory' to the climate system, causing important variations in the climate and ecological conditions on long-time-scales."

Todd-Brown *et al*. (2013) point out, "because future climate projections depend on the carbon cycle, ESMs [Earth System Models] must be capable of accurately representing the pools and fluxes of carbon in the biosphere, particularly in soils that store a large fraction of terrestrial organic carbon," but they note "there have been few quantitative assessments of ESM skill in predicting soil carbon stocks, contributing to uncertainty in model simulations." "To help reduce this uncertainty," as Todd-Brown *et al*. describe it, they "analyzed simulated soil carbon from ESMs participating in the Fifth Climate Model Intercomparison Project (CMIP5)," comparing the results from 11 model centers to empirical data obtained from the Harmonized World Soil Database (HWSD) and the Northern Circumpolar Soil Carbon Database (NCSCD). According to the seven scientists, some ESMs "simulated soil carbon stocks consistent with empirical estimates at the global and biome scales," but all of the models "had difficulty representing soil carbon at the 1° scale." They note, "despite similar overall structures, the models do not agree well among themselves or with empirical data on the global distribution of soil carbon." Todd-Brown *et al*. conclude "all model structures may have serious shortcomings, since net primary productivity and temperature strongly influenced soil carbon stocks in ESMs but not in observational data."

Todd-Brown *et al*. outline what may need to be done in order to resolve the failure of ESMs to adequately replicate the real world, including "better prediction of soil carbon drivers, more accurate model parameterization, and more comprehensive representation of critical biological and geochemical mechanisms in soil carbon sub-models."

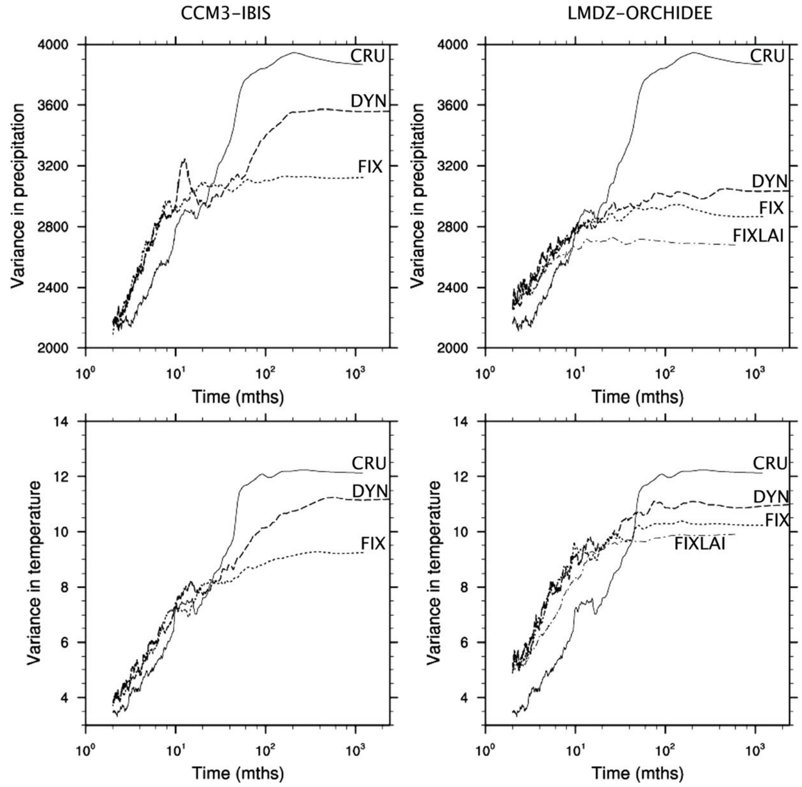

Figure 1.3.9.1. Power spectra of precipitation (top) and temperature (bottom) for the CCMv3-IBIS (left) and LMDz-ORCHIDEE (right) model systems. The solid line represents data from the Hadley Centre (observed), and the dashed (dotted) line represents dynamic [DYN] (fixed [FIX]) vegetation. Reprinted with permission from Delire, C., De Noblet-Ducoudre, N., Sima, A., and Gouriand, I. 2011. Vegetation dynamics enhancing long-term climate variability confirmed by two models. *Journal of Climate* **24**: 2238–2257.

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1.3.10 Permafrost

Almost all assessments of the potential impacts of climate change on the world's permafrost are based on a two-layer model that incorporates a seasonally frozen active layer and an underlying perennially frozen soil. Shur *et al*. (2005) examined the virtues of adding a transition zone layer to produce a more realistic three-layer model.

Through a review of the literature and theoretical and data analyses, Shur *et al*. showed, among other things, that the transition zone alternates between seasonally frozen ground and permafrost over sub-decadal to centennial time scales, functioning as a buffer between the active layer and the underlying perennial permafrost by increasing the latent heat required for thaw. Consequently, in the words of Shur *et al*., use of a two-layer conceptual model in permafrost studies "obscures effective understanding of the formation and properties of the upper permafrost and syngenetic permafrost, and makes a realistic determination of the stability of arctic geosystems under climatic fluctuations virtually impossible." They conclude "the impacts of possible global warming in permafrost regions cannot be understood fully without consideration of a more realistic three-layer model."

In light of the authors' findings, it would appear two-layer model forecasts of future permafrost trends under various global warming scenarios are inadequate. And if the transition zone does indeed act as a buffer at sub-decadal to centennial time scales, then current permafrost trends are likely to be manifestations of past climatic trends, some of which may have taken place several decades ago or more.

Koven *et al*. (2013) note "permafrost is a critical component of high-latitude land and determines the character of the hydrology, ecology, and biogeochemistry of the region." Therefore, they write, there is "widespread interest in the use of coupled atmosphere-ocean-land surface models to predict the fate of permafrost over the next centuries because (1) permafrost contains the largest organic carbon (C) reservoir in the terrestrial system (Tarnocai *et al*., 2009), (2) permafrost stability is primarily dependent on temperature, and (3) global warming is expected to be relatively larger over the permafrost domain because of arctic amplification processes (Holland and Bitz, 2003)."

Koven *et al*. analyzed "output from a set of Earth system models (ESMs) that participated in phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al*., 2009) to evaluate the permafrost model predictions against observations and theoretical expectations and to compare the predicted fate of permafrost under warming scenarios." The three U.S. researchers revealed "the models show a wide range of behaviors under the current climate, with many failing to agree with fundamental aspects of the observed soil thermal regime at high latitudes."

Koven *et al*. report, "under future climate change, the models differ in their degree of warming, both globally and at high latitudes, and also in the response of permafrost to this warming." They note "there is a wide range of possible magnitudes in their responses, from 6% to 29% permafrost loss per 1°C high-latitude warming." Several of the models, they report, "predict substantial permafrost degradation has already occurred (ranging from 3% gain to 49% loss relative to 1850 conditions)" and "the majority of models at the high end of relative twentieth-century permafrost loss also show unrealistically small preindustrial permafrost extent." They also note "there is wide model disagreement on the value of the difference in mean temperature across the air-soil interface, with several of the models [even] predicting the wrong sign for this statistic" and "there is wide model disagreement in the changes of [the] mean and [the] amplitude of soil temperatures with depth."

Koven *et al*. conclude by stating, "with this analysis, we show that widespread disagreement exists among this generation of ESMs," once again suggesting current Earth system models are not yet accurate enough for real-world application.

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1.3.11 Miscellaneous

Several other studies have documented inadequacies in climate model projections. This subsection highlights those that do not quite fit in other subsections of Section 1.4 or that deal with multiple climatic elements and, as such, are best suited for this miscellaneous category.

"Climate variability," in the words of Latif and Keenlyside (2011), "can be either generated internally by interactions within or between the individual climate subcomponents (e.g., atmosphere, ocean and sea ice) or externally by e.g., volcanic eruptions, variations in the solar insolation at the top of the atmosphere, or changed atmospheric greenhouse gas concentrations in response to anthropogenic emissions." Some examples of these internal variations are "the North Atlantic Oscillation (NAO), the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Variability (PDV), and the Atlantic Multidecadal Variability (AMV)," all of which "project on global or hemispheric surface air temperature (SAT), thereby masking anthropogenic climate change."

In a review of this complex subject, Latif and Keenlyside—who hold positions at Germany's Leibniz-Institute for Meerewissenschaften at the University of Kiel—first describe various mechanisms responsible for internal variability, giving special attention to the variability of the Atlantic Meridional Overturning Circulation (AMOC), which they suggest is likely the origin of a considerable part of the decadal variability within the Atlantic Sector, after which they discuss the challenge of decadal SAT predictability and various factors limiting its realization.

The two researchers identify numerous problems that hamper decadal climate predictability, including that "the models suffer from large biases." In the cases of annual mean sea surface temperature (SST) and SAT over land, for example, they state "typical errors can amount up to 10°C in certain regions," as Randall *et al*. (2007) found to be the case for many of the IPCC-AR4 models. Latif and Keenlyside also note several models "fail to simulate a realistic El Niño/Southern Oscillation." In addition, the researchers point out "several assumptions have generally to be made about the process under consideration that cannot be rigorously justified, and this is a major source of uncertainty."

Another problem they discuss is that "some components of the climate system are not well represented or not at all part of standard climate models," one example being the models' neglect of the stratosphere. This omission is serious; Latif and Keenlyside say "recent studies indicate that the mid-latitudinal response to both tropical and extra-tropical SST anomalies over the North Atlantic Sector may critically depend on stratospheric feedbacks," noting Ineson and Scaife (2009) present evidence for "an active stratospheric role in the transition to cold conditions in northern Europe and mild conditions in southern Europe in late winter during El Niño years."

An additional common model shortcoming, even in standalone integrations with models forced by observed SSTs, is that model simulations of rainfall in the Sahel "fail to reproduce the correct magnitude of the decadal precipitation anomalies." Still another failure, as shown by Stroeve *et al*. (2007), is that "virtually all climate models considerably underestimate the observed Arctic sea ice decline during the recent decades in the so-called 20th century integrations with prescribed (known natural and anthropogenic) observed forcing." In addition, "atmospheric chemistry and aerosol processes are still not well incorporated into current climate models."

In summing up their findings, which include those noted above and many more, Latif and Keenlyside state, "a sufficient understanding of the mechanisms of decadal-to-multidecadal variability is lacking." They note "state-of-the-art climate models suffer from large biases" and "are incomplete and do not incorporate potentially important physics." Various mechanisms "differ strongly from model to model," they point out; "the poor observational database does not allow a distinction between 'realistic' and 'unrealistic' simulations"; and many models "still fail to simulate a realistic El Niño/Southern Oscillation." Therefore, they conclude, "it cannot be assumed that current climate models are well suited to realize the full decadal predictability potential"—a somewhat obscure way of stating current state-of-the-art climate models are not good enough to make reasonably accurate simulations of climate change over a period of time (either in the past or the future) that is measured in mere decades.

In another paper, Lucarini *et al*. (2007) compared for the period 1962–2000 "the estimate of the northern hemisphere mid-latitude winter atmospheric variability within the available 20th century simulations of 19 global climate models included in the Intergovernmental Panel on Climate Change [IPCC] 4th Assessment Report" with "the NCEP-NCAR and ECMWF reanalyses," compilations of real-world observations produced by the National Center for Environmental Prediction (NCEP), in collaboration with the National Center for Atmospheric Research (NCAR), and by the European Center for Mid-Range Weather Forecast (ECMWF). The five Italian researchers report "large biases, in several cases larger than 20%, are found in all the considered metrics between the wave climatologies of most IPCC models and the reanalyses, while the span of the climatologies of the various models is, in all cases, around 50%." They also report "the traveling baroclinic waves are typically overestimated by the climate models, while the planetary waves are usually underestimated," and "the model results do not cluster around their ensemble mean." The authors conclude by stating, "this study suggests caveats with respect to the ability of most of the presently available climate models in representing the statistical properties of the global scale atmospheric dynamics of the present climate and, *a fortiori* ["all the more," as per Webster's Dictionary], in the perspective of modeling climate change."

According to Scherrer (2011), "climate model verification primarily focused [in the past] on the representation of climatological means." But "on the other hand," he continues, "a good representation of second-order moments (i.e., variability) on different time scales (e.g., daily, month-to-month, or interannual, etc.) is crucial and probably provides an even better test as to whether [real-world] physical processes are well represented in the models." Working with twentieth century climate model runs prepared within the context of the IPCC AR4 assessment (now called the CMIP3 data set), Scherrer set out to compare model simulations of the interannual variability (IAV) of 2-m-height air temperature (*T*), sea level pressure (*SLP*), and precipitation (*P*) over the twentieth century with observational and reanalysis data sets for the same time period using standard deviation-based variability indices.

The Swiss scientist describes a number of problems he encountered with the CMIP3 models. With respect to *SLP*, the situation was pretty good: "only minor IAV problems are found." With respect to temperature, however, differences between observations and models are, in general, "larger than those for *SLP*." And for precipitation, "IAV is 'all over the place' and no clear relations with *T* and *SLP* IAV problems can be established."

Concentrating thereafter mostly on temperature, Scherrer notes "a few models represent *T* IAV much worse than others and create spurious relations of IAV representation and the climate change signal." Among the "better" IAV models, he finds "the 'good' IAV models in the tropics are in general not also the 'good' IAV models in the extra-tropics," and "the 'good' IAV models over the sea are in general not the 'good' IAV models over land." He further notes "similar results are found for the relation between *T* IAV representation and the amplitude of projected changes in temperature."

"In general," Scherrer writes, "it is concluded that, aggregated over very large regions, hardly any robust relations exist between the models' ability to correctly represent IAV and the projected temperature change." He says these results represent "a plea to remove the 'obviously wrong' models (e.g., like those that have sea ice extending to below 50°N in the Atlantic and DJF temperature biases of ~40°C in Iceland, cf. Raisanen, 2007) before doing climate analyses."

de Boer *et al*. (2012) point out "observed and projected changes in the Arctic region are some of the most striking concerns surrounding climate trends," noting the latter "likely have important consequences both within the Arctic and globally." They further note "a new generation of Earth system models has been utilized to prepare climate projections for the fifth phase of the Coupled Model Intercomparison Project (CMIP5)," the results of which are planned to be used "in the Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report* (AR5)." They set out to determine how well these models perform, but the closest they could come to conducting such a test was to interrogate the models used in the AR4 report of the IPCC. Thus, de Boer *et al*. simulated key features of the Arctic atmosphere in the Community Climate System Model, version 4 (CCSM4) and compared the results of those simulations "against observational and reanalysis datasets for the present-day (1981–2005)."

Describing problems they encountered in this endeavor, the seven scientists report "simulated surface air temperatures are found to be slightly too cold," "evaluation of the sea level pressure [SLP] demonstrates some large biases, most noticeably an under simulation of the Beaufort High during spring and autumn," "monthly Arctic-wide [SLP] biases of up to 13 mb are reported," "cloud cover is under-predicted for all but summer months," and "cloud phase is demonstrated to be different from observations." They also found "simulated all-sky liquid water paths are too high," "ice water path was generally too low," and "precipitation is found to be excessive over much of the Arctic compared to ERA-40 and the Global Precipitation Climatology Project estimates." They report "biases of 40%-150% are calculated over northern North America, northern Greenland, and the Arctic Ocean," while "over the Norwegian Sea ... evaporation is over-simulated by up to 3.5 mm/day," such that "P-E is generally too high over much of the Arctic, particularly over coastal Greenland."

de Boer *et al*. also found "CCSM4 over-predicts surface energy fluxes during summer months" and "under-predicts it during winter." They also report "the strengths of surface inversions were found to be too great in CCSM4 when compared to ERA-40, with distributions showing a near-doubling of strength," and (15) "CCSM4 is found to have more inversions than ERA-40 for all months."

Oddly, de Boer *et al*. conclude "CCSM4 provides a consistent representation of present-day Arctic climate" and "in doing so it represents individual components of the Arctic atmosphere with respectable accuracy." This statement seems to us to be an egregious misuse of the word "respectable."

Blazquez and Nuñez (2013) point out "the first step to understand climate changes that are likely to occur in the future is the assessment of the present climate," which "allows determining the model deficiencies." The two authors set out to "[evaluate] a present climate simulation over southern South America performed with the Meteorological Research Institute/Japanese Meteorological Agency (MRI/ JMA) high resolution global model."

Comparing their simulated wind results with data from the European Centre Medium Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA 40), and their temperature and precipitation simulations with data from various meteorological stations, the two Argentinian researchers report discovering significant model deficiencies: Speeds of the low level jet and the westerlies "are generally underestimated" and at upper levels "the westerlies are overestimated over central Argentina." During December-February, March-May, and September-November, they report, "the MRI/JMA global model underestimates the temperature over east of Argentina, west of Uruguay, south of Chile and over tropical latitudes" and "overestimates are observed over central Argentina," while "in June-August the model underestimates the temperature over most of Argentina, south of Chile and to the north of 20°S." They also found "the model overestimates temperature interannual variability in all regions and all seasons, except in [June-July-August]."

With respect to precipitation, the authors found in all seasons the model yields "an underestimation of the precipitation in the southeast of Brazil and south of Peru and an overestimation in Bolivia, Uruguay, north and central Chile and north of Peru," and during "the dry season (JJA) the model greatly overestimates the precipitation over northeastern and central Argentina." They note "in regions located over mountainous areas the model presents a poor reproduction of the annual cycle" and "observed precipitation trends are generally positive whereas simulated ones are negative."

Landrum *et al*. (2013) compared Last Millennium (LM) simulations of the Community Climate System Model, version 4 (CCSM4) to real-world "data reconstructions of temperature, the hydrologic cycle, and modes of climate variability." In addition to some successes of the CCSM4, the seven scientists report a number of failures. They note "the LM simulation does not reproduce La Niña-like cooling in the eastern Pacific Ocean during the MCA [Medieval Climate Anomaly] relative to the LIA [Little Ice Age], as has been suggested by proxy reconstructions," and "patterns of simulated precipitation change for the Asian monsoon to large volcanic eruptions have nearly opposite anomalies from those reconstructed from tree-ring chronologies." They report CCSM4 "does not simulate a persistent positive NAO [North Atlantic Oscillation] or a prolonged period of negative PDO [Pacific Decadal Oscillation] during the MCA, as suggested by some proxy reconstructions" and "the model simulates cooling of ~1.0°-1.5°C after the large eruptions of the late thirteenth, mid-fifteenth, late eighteenth, and early nineteenth centuries, 2-3 times larger than the NH [Northern Hemisphere] summer anomalies estimated from tree-ring or multiproxy reconstructions." They further report "twentieth-century simulations indicate that the CCSM4 hemispheric response to volcanic eruptions is stronger than observed (Meehl *et al*., 2012)" and they "do not find a persistent positive NAO or a prolonged period of negative PDO during the MCA suggested by the proxy reconstructions (MacDonald and Case, 2005; Trouet *et al*., 2009)."

Su *et al*. (2013) evaluated "the performance of 24 GCMs available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) … over the eastern Tibetan Plateau (TP) by comparing the model outputs with ground observations for the period 1961–2005," focusing their attention on temperature and precipitation. The five researchers report that with respect to temperature, "most GCMs reasonably capture the climatological patterns and spatial variations of the observed climate," but "the majority of the models have cold biases, with a mean underestimation of 1.1°-2.5°C for the months December-May, and less than 1°C for June-October." As for precipitation, they state "the simulations of all models overestimate the observations in climatological annual means by 62.0%-183.0%," while noting "only half of the 24 GCMs are able to reproduce the observed seasonal pattern," including "the sharp contrast between dry winters and wet summers." The last of these observations clearly suggests, as Su *et al*. note, that there is "a critical need to improve precipitation-related processes in these models." They found 90-year forward projections of both precipitation and temperature "differ much more among various models than among emissions scenarios," suggesting temperature-related processes in the models must be improved upon as well.

In a paper published in *Nature Climate Change*, Knutti and Sedlacek (2013) write "estimates of impacts from anthropogenic climate change rely on projections from climate models," but "uncertainties in those have often been a limiting factor, particularly on local scales." They note "a new generation of more complex models running scenarios for the upcoming Intergovernmental Panel on Climate Change *Fifth Assessment Report* (IPCC AR5) is widely, and perhaps naively, expected to provide more detailed and more certain projections."

Exploring whether these expectations are being met, the two researchers performed "a first comparison between projections from CMIP3 and CMIP5," in order to see to what extent real progress in the modeling of Earth's global climate may have been made. Knutti and Sedlacek report "projected global temperature change from the new models is remarkably similar to that from those used in IPCC AR4 after accounting for the different underlying scenarios" and "the local model spread has not changed much despite substantial model development and a massive increase in computational capacity." They write "there is … little evidence from CMIP5 that our ability to constrain the large-scale climate feedbacks has improved significantly"; "model mean patterns of temperature and precipitation change … are remarkably similar in CMIP3 and CMIP5"; and "robustness over land is slightly higher but also similar in CMIP3 and CMIP5," which they describe as "troublesome."

In light of these findings, and "if the past is a guide to the future," as the two researchers put it, "then uncertainties in climate change are unlikely to decrease quickly, and may even grow temporarily." The scientists say they "have illustrated this for seasonal temperature and precipitation" and "it is likely that impact-relevant predictions, for example of extreme weather events, may be even harder to improve."

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1.4 Large Scale Phenomena and Teleconnections

The role of irregular interannual and interdecadal climate variations in forcing climate change is now being quantified by climate science. Some specific variations—the Pacific Decadal Oscillation (PDO), for example—have been identified and evaluated, and they correlate well with decadal changes in global temperatures throughout the twentieth century. Other variations—such as the El Niño and Southern Oscillation (ENSO)—have been recognized for decades.

Although scientists can explain the role of these circulations in local climate variability and understand their dynamic evolution, the trigger mechanisms for initiating changes in these oscillations are not well understood. We use climate models to improve our understanding of them. A model, however, cannot replicate the basic flow adequately. A by-product of this failure is that model output can have significant biases, a problem weather forecasters have recognized for decades.

This section examines several of these features of Earth's climate and how well they are simulated by the models. Many such studies are highlighted in the subsections below; many more were addressed in earlier sections of this chapter, including the sections on oceans, temperature, and precipitation.

1.4.1 El Niño/Southern Oscillation

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. This section highlights findings that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality, beginning with several studies that described the status of the problem a decade ago.

In a comparison of 24 coupled ocean-atmosphere climate models, Latif *et al.* (2001) report, "almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology." They also note, "only a few of the coupled models simulate the El Niño/Southern Oscillation in terms of gross equatorial SST anomalies realistically." And they state, "no model has been found that simulates realistically all aspects of the interannual SST variability." Consequently, because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," according to Fedorov and Philander (2000), and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising the researchers conclude climate models near the turn of the century did not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also played a role in those models' failure to simulate ENSO. According to Overpeck and Webb (2000), there was evidence that "ENSO may change in ways that we do not yet understand," and these "ways" clearly had not yet been modeled. White *et al.* (2001), for example, found "global warming and cooling during Earth's internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance"; they note these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) made a case for a lunar forcing of ENSO activity, a factor not included in any climate model of that time.

Another example of the inability of the most sophisticated of late twentieth century climate models to properly describe El Niño events was provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997–98 El Niño. They found the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from zero to eight months. They also determined no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium-range lead time of six to 11 months. Hence, they state, "since no models were able to provide useful predictions at the medium and long ranges, there were no models that provided both useful and skillful forecasts for the entirety of the 1997–98 El Niño."

It is little wonder several scientists criticized model simulations of ENSO behavior at the turn of the century, including Walsh and Pittock (1998), who conclude, "there is insufficient confidence in the predictions of current models regarding any changes in ENSO" and Fedorov and Philander (2000), who wrote, "at this time, it is impossible to decide which, if any, are correct."

The rest of this section considers whether the situation has improved over the past decade.

Huber and Caballero (2003) introduce their contribution to the subject by stating, "studies of future transient global warming with coupled ocean-atmosphere models find a shift to a more El Niño-like state," although they also report the "permanent El Niño state"—which has been hypothesized by some in the climate community—"is by no means uniformly predicted by a majority of models." To help resolve this battle of the models, they worked with still another model plus real-world data pertaining to the Eocene, the past geologic epoch—much warmer than the recent past—which provided, in their words, "a particularly exacting test of the robustness of ENSO." They used the Community Climate System Model of the National Center for Atmospheric Research, which they state yielded "a faithful reproduction of modern-day ENSO variability," to "simulate the Eocene climate and determine whether the model predicts significant ENSO variability." In addition, they compared the model results against middle Eocene lake-sediment records from the Lake Gosiute complex in Wyoming and Eckfield Maar in Germany.

Huber and Caballero report the model simulations showed "little change in ... ENSO, in agreement with proxies." They also note other studies "indicate an ENSO shutdown as recently as ~6000 years ago, a period only slightly warmer than the present." They conclude "this result contrasts with theories linking past and future 'hothouse' climates with a shift toward a permanent El Niño-like state."

Three years later, Joseph and Nigam (2006) evaluated several climate models "by examining the extent to which they simulated key features of the leading mode of interannual climate variability: El Niño-Southern Oscillation (ENSO), which they describe as "a dominant pattern of ocean-atmosphere variability with substantial global climate impact," based on "the Intergovernmental Panel on Climate Change's (IPCC) *Fourth Assessment Report* (AR4) simulations of twentieth-century climate." Different models were found to do well in some respects but not so well in others. For example, they found climate models "are still unable to simulate many features of ENSO variability and its circulation and hydroclimate teleconnections." They found the models had only "begun to make inroads in simulating key features of ENSO variability."

The two scientists say their study suggests "climate system models are not quite ready for making projections of regional-to-continental scale hydroclimate variability and change" and "predicting regional climate variability/change remains an onerous burden on models."

One year later, L'Ecuyer and Stephens (2007) asked how well state-of-the-art climate models reproduced the workings of real-world energy and water cycles, noting "our ability to model the climate system and its response to natural and anthropogenic forcings requires a faithful representation of the complex interactions that exist between radiation, clouds, and precipitation and their influence on the large-scale energy balance and heat transport in the atmosphere," further stating "it is also critical to assess [model] response to shorter-term natural variability in environmental forcings using observations."

The two researchers used multi-sensor observations of visible, infrared, and microwave radiance obtained from the Tropical Rainfall Measuring Mission satellite for the period January 1998 through December 1999 in order to evaluate the sensitivity of atmospheric heating (and the factors that modify it) to changes in east-west SST gradients associated with the strong 1998 El Niño event in the tropical Pacific, as expressed by the simulations of nine general circulation models of the atmosphere utilized in the IPCC's AR4. This protocol, in their words, "provides a natural example of a short-term climate change scenario in which clouds, precipitation, and regional energy budgets in the east and west Pacific are observed to respond to the eastward migration of warm sea surface temperatures."

L'Ecuyer and Stephens report "a majority of the models examined do not reproduce the apparent westward transport of energy in the equatorial Pacific during the 1998 El Niño event." They also discovered "the intermodel variability in the responses of precipitation, total heating, and vertical motion [was] often larger than the intrinsic ENSO signal itself, implying an inherent lack of predictive capability in the ensemble with regard to the response of the mean zonal atmospheric circulation in the tropical Pacific to ENSO." In addition, they found "many models also misrepresent the radiative impacts of clouds in both regions [the east and west Pacific], implying errors in total cloudiness, cloud thickness, and the relative frequency of occurrence of high and low clouds." In light of these much-less-than-adequate findings, they conclude, "deficiencies remain in the representation of relationships between radiation, clouds, and precipitation in current climate models," further stating these deficiencies "cannot be ignored when interpreting their predictions of future climate."

Paeth *et al.* (2008) compared 79 coupled ocean-atmosphere climate simulations derived from 12 different state-of-the-art climate models forced by six IPCC emission scenarios with observational data in order to evaluate how well they reproduced the spatio-temporal characteristics of ENSO over the twentieth century, after which they compared the various models' twenty-first century simulations of ENSO and the Indian and West African monsoons to one another.

With respect to the twentieth century, this work revealed "all considered climate models draw a reasonable picture of the key features of ENSO." With respect to the twenty-first century, on the other hand, they note "the differences between the models are stronger than between the emission scenarios," while "the atmospheric component of ENSO and the West African monsoon are barely affected." Their "overall conclusion" is that "we still cannot say much about the future behavior of tropical climate." They consider their study to be merely "a benchmark for further investigations with more recent models in order to document a gain in knowledge or stagnation over the past five years."

Jin *et al*. (2008) investigated the overall skill of ENSO prediction in retrospective forecasts made with ten different state-of-the-art ocean-atmosphere coupled general circulation models with respect to their ability to hindcast real-world observations for the 22 years from 1980 to 2001. They found almost all models have problems simulating the mean equatorial SST and its annual cycle. They write, "none of the models we examined attain good performance in simulating the mean annual cycle of SST, even with the advantage of starting from realistic initial conditions." They also note, "with increasing lead time, this discrepancy gets worse" and "the phase and peak amplitude of westward propagation of the annual cycle in the eastern and central equatorial Pacific are different from those observed." They also found "ENSO-neutral years are far worse predicted than growing warm and cold events" and "the skill of forecasts that start in February or May drops faster than that of forecasts that start in August or November." They and others call this behavior "the spring predictability barrier." Jin *et al*. conclude, "accurately predicting the strength and timing of ENSO events continues to be a critical challenge for dynamical models of all levels of complexity."

McLean *et al.* (2009) quantified "the effect of possible ENSO forcing on mean global temperature, both short-term and long-term," using Southern Oscillation Index (SOI) data provided by the Australian government's Bureau of Meteorology. This parameter was defined as "the standardized anomaly of the seasonal mean sea level pressure difference between Tahiti and Darwin, divided by the standard deviation of the difference and multiplied by 10." The temperature data employed in this endeavor were "the University of Alabama in Huntsville lower-tropospheric (LT) temperature data based on measurements from selected view angles of Microwave Sounding Unit (MSU) channel LT 2" for the period December 1979 to June 2008, supplemented by "balloon-based instrumentation (radiosondes)." For the latter data, dating back to 1958, they employed the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) product (A) of the U.S. National Climatic Data Center, which represents the atmospheric layer between approximately 1,500 and 9,000 meters altitude.

McLean *et al*. found "change in SOI accounts for 72% of the variance in GTTA [Global Tropospheric Temperature Anomalies] for the 29-year-long MSU record and 68% of the variance in GTTA for the longer 50-year RATPAC record," as well as "81% of the variance in tropospheric temperature anomalies in the tropics," where they note ENSO "is known to exercise a particularly strong influence." In addition, they determined "shifts in temperature are consistent with shifts in the SOI that occur about 7 months earlier." The three researchers conclude, "natural climate forcing associated with ENSO is a major contributor to variability and perhaps recent trends in global temperature, a relationship that is not included in current global climate models."

Harmonic analysis is useful in this discussion because it can be used to construct models of time series or spatial patterns. It also can be used as a diagnostic tool on the same type of data sets. Harmonics are natural solutions to differential equations that represent the motion in oscillating systems and take the form of waves, usually represented as trigonometric functions (for example sine or cosine). Harmonics simply represent the transformation of data from Cartesian coordinates (space and/or time) to a wave coordinate. Thus, "wave-like" phenomena not readily apparent to the eye, or which appear as random noise, can be identified in a data set.

The El Niño (warm East Pacific tropical water temperatures)/La Niña (cold East Pacific tropical water temperatures) phenomenon is known to occur in a quasi-cyclic fashion repeating every two to seven years. It is the leading reason for the global variation in temperatures and precipitation on an interannual time scale. Conceptual models and general circulation models (GCMs) have been used to hypothesize that El Niño may arise as a result of internal nonlinear processes.

White and Liu (2008) found El Niño/La Niña pairs may be "phase locked" to the quasi-decadal oscillation (QDO), which is linked to the 11-year solar cycle. Phase locking means two different harmonics vary in the same way with respect to each other. The simplest example of this is pure "constructive" or "destructive" interference. The authors performed harmonic analysis on a time series of Pacific region sea surface temperatures (SSTs) for 1895–2005. They also gathered 110 years of data from a multi-century run of a coupled atmosphere-ocean GCM corresponding to the observations.

The authors found an 11-year QDO cycle in the observed record as well as strong peaks in the years associated with El Niño, especially at 3.6 and 2.2 years. When the authors ran the GCM without the 11-year solar forcing, the computer model could not reproduce the QDO in its SST record. When the GCM included the forcing, the model not only reproduced the QDO but also the strong peaks in the 3.6 and 2.2 year period similar to observations.

White and Liu also found a "phase locking" of the 11-year cycle with the 3.6 and 2.2 year cycles in both the model and the observations. This suggests the higher frequency oscillations had higher amplitudes in step with the lower frequency one and are "hitting" a maximum (minimum) roughly in correspondence with the low frequency cycle.

White and Liu went further with their analysis, taking the nine 11 year cycles found in each record and "compositing" them (Figure 1.4.1.1). In both the model and observations, similar behavior was observed. When the 11, 3.6, and 2.2 (ridge—warm—El Niño / trough—cold—La Niña) year cycles were added together and superimposed on the 11-year cycle as a visual aid, it was apparent El Niño/La Niña couplets occurred together on the ascending and descending side of the QDO, but that a strong El Niño (La Niña) also can occur at the peak (in the valley) of the QDO.

Finally, White and Liu used the previously derived QDO model of Jin (1997) and incorporated their findings, finding a pattern similar to that shown in Figure 1.4.1.1. They also used the 3.6 and 2.2 year harmonics to compare to the observed record with the 11-year cycle filtered out. They found this combination reliably identified 26 of 32 El Niño events of 1895–2005.

The authors therefore provide convincing evidence the 11-year solar cycle may be the trigger for El Niño/La Niña events. By using harmonic analysis on observed and model data, they found similar El Niño-related behavior in each, meaning "the solar forced QDO forces the ~3.6 year ENSO signal; which in turn forces the ~2.2 year ENSO signal, and so on." There are two important results to take away from this work: Models that include solar forcing have become more proficient at capturing interannual variability, and El Niño and La Niña onsets may be somewhat predictable even 10 years in advance. Such developments would be a boon for long-range forecasting.

In a review paper two years later, Vecchi and Wittenberg (2010) "[explored] our current understanding of these issues," stating it is "of great interest to understand the character of past and future ENSO variations." The two researchers at the U.S. National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory point out "the amplitude and character of ENSO have been observed to exhibit substantial variations on timescales of decades to centuries" and "many of these changes over the past millennium resemble those that arise from internally generated climate variations in an unforced climate model." In addition, they report "ENSO activity and characteristics have been found to depend on the state of the tropical Pacific climate system, which is expected to change in the 21st century in response to changes in radiative forcing and internal climate variability." The two

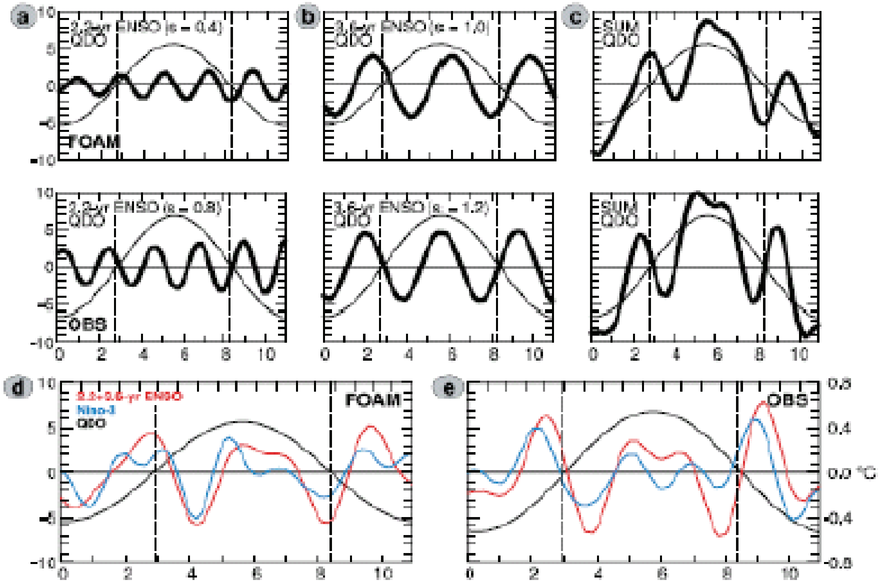

Figure 1.4.1.1. The nine member composites of each 11-year QDO cycle for the observations (obs) and the GCM (FOAM): (a) is the QDO (thin) and 2.2 year El Niño (thick), (b) is the same as (a) except for the 3.6 year cycle, and (c) is the sum of the three cycles (thick) shown against the 11 year cycle (thin). For (d) and (e) the figure shows the sum of the 2.2 and 3.6 year cycle against the entire record and the 11 year cycle for the (d) model, and (e) observations. Reprinted with permission from White, W.B. and Liu, Z. 2008. Non-linear alignment of El Niño to the 11-yr solar cycle. *Geophysical Research Letters,* **35,** L19607, doi:10.1029/2008GL034831.

scientists also note "the extent and character of the response of ENSO to increases in greenhouse gases are still a topic of considerable research" and "given the results published to date, we cannot yet rule out possibilities of an increase, decrease, or no change in ENSO activity arising from increases in CO_2."

Vecchi and Wittenberg conclude their review of the subject by stating "we expect the climate system to keep exhibiting large-scale internal variations," but they add, "the ENSO variations we see in decades to come may be different than those seen in recent decades." They admit "we are not currently at a state to confidently project what those changes will be."

Catto *et al*. (2012a) write "the El Niño-Southern Oscillation (ENSO) is linked to the interannual climate variability of Australia, in part through its effect on the sea surface temperatures (SSTs) around northern Australia," as has been documented by Hendon (2003) and Catto *et al*. (2012b). They explain "it is important that global coupled climate models are able to represent this link between ENSO and north Australian SSTs so that we can have more confidence in the projections of future climate change for the Australian region." For the authors' contribution to the topic, "the link between ENSO and north Australian SSTs has been evaluated in the models participating in CMIP5 with a view to comparing them with the CMIP3 models evaluated in Catto *et al*. (2012b)."

The three Australian researchers' study revealed "the CMIP5 models still show a wide range in their ability to represent both ENSO events themselves, and their relationship to north Australian SST"; "most of the models fail to capture the strong seasonal cycle of correlation between the Niño-3.4 and north Australian SSTs"; and "the models in general are still missing some underlying process or mechanism." Catto *et al*. conclude, "gaining a deeper understanding of the physical mechanism behind the strong link between the SSTs in the Niño-3.4 region and to the north of Australia using these models" is "a vital next step" for this work, which they state is required "to elucidate the processes missing from the models that cannot capture the link."

Zhang and Jin (2012) indicate "ENSO behaviors in coupled models have been widely evaluated," citing Neelin *et al*. (1992), Delecluse *et al*. (1998), Latif *et al*. (2001), Davey *et al*. (2002), AchuataRao and Sperber (2002, 2006), Capotondi *et al*. (2006), Guilyardi (2006), and Zhang *et al*. (2010). However, they write, "coupled models still exhibit large biases in modeling the basic features of ENSO," citing Guilyardi *et al*. (2009). Among these biases is "a sea surface temperature (SST) anomaly (SSTA) too tightly confined to the equator (e.g., Stockdale *et al*., 1998; Kang *et al*., 2001)." More specifically, and recently, they say, "it was shown that the ENSO meridional width in the models participating in Phase 3 of the Coupled Model Inter-comparison Project (CMIP3) is only about two thirds of what is observed," citing Zhang *et al*. (2012).

Zhang and Jin ask the obvious question: "Does the systematical narrow bias in ENSO width still exist in current models developed for Phase 5 of the CMIP (CMIP5)?" They answer the question by assessing the ENSO meridional widths simulated by 15 CMIP5 models and 15 CMIP3 models for the period 1900–1999, comparing the results of both groups against observation-based monthly SST data from the Hadley Center Sea Ice and Sea Surface Temperature (HadISST) data of Rayner *et al*. (2003). The analysis indicated "a systematic narrow bias in ENSO meridional width remains in the CMIP5 models," although they state the newest results represent "a modest improvement over previous models." Is a modest improvement good enough? That question remains to be answered.

Roxy *et al*. (2013) point out recent studies have highlighted the existence of a new phenomenon, referred to as the El Niño Modoki, characterized by a warm sea surface temperature (SST) anomaly in the central equatorial Pacific and a cold SST anomaly in the western and eastern Pacific. Some observers of this phenomenon have argued "the increasing frequency of the El Niño Modoki in recent decades is due to global warming." Roxy *et al*., considering it imperative to examine the changing teleconnection between ENSO/Modoki and the Indian summer monsoon, revisited "climate change experiments under the fourth *Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC), namely the twentieth century simulations (20C3M) and Special Report on Emissions Scenarios (SRES) A1B, … to study whether these models can reproduce the ENSO and ENSO Modoki patterns" and "their teleconnections with the Indian summer monsoon, and also the implications for the future."

The four researchers from India report "only ~1/4th of the models from 20C3M capture either ENSO or ENSO Modoki patterns in June, July, August and September." They note "of this 1/4th, only two models simulate both ENSO and ENSO Modoki patterns as important modes" and "of these two, only one model simulates both ENSO and ENSO Modoki as important modes during both summer and winter." In addition, they note the two models that demonstrate ENSO Modoki, as well as ENSO associated variance in both 20C3M and SRES A1B, project the *opposite* types of impacts of SRES A1B.

Roxy *et al*. say their findings are indicative of "the challenges associated with the limitations of the models in reproducing the variability of the monsoons and ENSO flavors, not to speak of failing in capturing the potential impacts of global warming as they are expected to."

Koumoutsaris (2013) reports, "currently, global climate models disagree in their estimates of feedbacks, and this is one of the main reasons for uncertainty in future climate projections," citing Bony *et al*. (2006). He further notes "in order to unveil the origin of these inter-model differences, model simulations need to be evaluated against observations of present climate." He estimated "the feedbacks from water vapor, lapse-rate, Planck, surface albedo and clouds, using models and observations based on the climate response over the last 30 years," short-term feedbacks that "result both from external changes in the forcing (due to greenhouse gas increases, volcanic and industrial aerosol emissions) and internal climate variations (mostly due to ENSO variability)." The Swiss scientist reports "the CMIP3 models show a much larger interdecile range for all short-term feedbacks in comparison to the long-term ones," which he states "is also the case for the three models with the most realistic ENSO representation," citing van Oldenborgh *et al*. (2005). He also indicates the models have difficulty capturing "the position and magnitude of ENSO teleconnection patterns." In addition, he reports "the uncertainty in the cloud feedback, using a combination of reanalysis and satellite data, is still very large."

Koumoutsaris concludes his analyses indicate "important aspects of the ENSO variability are still poorly understood and/or simulated." Regarding cloud feedback, he says it is difficult to come to "any firm conclusion," even as to the sign of the feedback." Clearly there remain multiple problems in the ability of models to reliably simulate various aspects of climate associated with ENSO events, casting further doubt on the overall ability of models to simulate the future climate of the planet in general.

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1.4.2 Atlantic and Pacific Ocean Multidecadal Variability (AMV)

The study of Semenov *et al.* (2010) shows natural variability contributed significantly to the warming period in the last few decades of the twentieth century and even may be responsible for the majority of the warming. The work of Petoukhov and Semenov (2010) has been cited as evidence that cold winters would be consistent with anthropogenic global warming. The reasoning follows this path: global warming in the Arctic would leave less sea ice, and with less sea ice, more heat is released to the air. As a result, continents could be colder since more moisture-laden air can mean more clouds and more snow, and thus colder temperatures over land. This is called the "Warm Arctic-Cold Continents" conjecture.

Semenov *et al.* (2010) first examined the results of several different model experiments performed by others, finding "North Atlantic sea surface temperature changes do project onto Northern Hemisphere and global surface air temperatures in these models," especially as these relate to the warming of the early twentieth century. They used the ECHAM5 model (European Centre for Medium Range Forecasting general circulation model, at the Max Planck Institute, Hamburg) and ran the model for 80 to 100 years using heat flux patterns (heat transport from the surface into the atmosphere or vice versa) related to the recent positive and negative extremes of the Atlantic Multidecadal Variability (AMV) for three differing regions in the North Atlantic and Arctic.

The authors' work demonstrated the AMV forced heat fluxes project statistically significant temperature and pressure changes onto the Northern Hemisphere climate, including influencing the NAO. The authors conclude, "the results show that such an internal and regionally confined climate variation can drive relatively large surface climate anomalies on regional, hemispheric, and even global scales. The Arctic plays an important role in this, explaining about 60% of the total Northern Hemisphere surface air temperature response." They also point out these results are applicable to recent decades. However, in their study the forcing of the Arctic on lower latitudes such as Europe is always in the same direction (warmer Arctic means warmer Europe), contradicting the "Warm Arctic-Cold Continents" conjecture.

The results of Semenov *et al*. and Petoukhov and Semenov are not surprising, as it has been theorized for some time that multidecadal oscillations, or natural variations, can imprint on regional, hemispheric, or even global climate change. However, in both studies, the modeling strategy is meant to test the sensitivity of the models to forced interdecadal variability. In neither study was the model able to capture interdecadal variability as it occurs in nature. Additionally, neither paper explicitly endorsed its results as being supportive of anthropogenic global warming as some have claimed. Although Semenov *et al.* are careful to add statements of assurance that their results do not contradict the global warming orthodoxy, they offer no evidence in support of it.

Lienert *et al*. (2011) state "climate models are increasingly being used to forecast future climate on time scales of seasons to decades," and "since the quality of such predictions of the future evolution of the PDO [Pacific Decadal Oscillation] likely depends on the models' ability to represent observed PDO characteristics, it is important that the PDO in climate models be evaluated."

Working with observed monthly-mean SST (sea surface temperature) anomalies they obtained from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version-1 (Rayner *et al*., 2003) data set for 1871–1999, as well as the extended reconstructed SST version-3b data set (Smith *et al*., 2008), Lienert *et al*. assessed the ability of 13 atmosphere-ocean global climate models from the third phase of the Coupled Model Intercomparison Project (CMIP3), conducted in support of the IPCC *Fourth Assessment Report* (Solomon *et al*., 2007), to "reproduce the observed relationship between tropical Pacific forcing associated with ENSO and North Pacific SST variability associated with the PDO."

The three Canadian researchers found "the simulated response to ENSO forcing is generally delayed relative to the observed response," a tendency they say "is consistent with model biases toward deeper oceanic mixed layers and weaker air-sea feedbacks." They found "the simulated amplitude of the ENSO-related signal in the North Pacific is overestimated by about 30%" and "model power spectra of the PDO signal and its ENSO-forced component are redder than observed because of errors originating in the tropics and extratropics."

Lienert *et al*. describe three implications of their findings. First, "because the simulated North Pacific response lags ENSO unrealistically, seasonal forecasts may tend to exhibit insufficient North Pacific responses to developing El Niño and La Niña events in the first few forecast months." Second, "at longer forecast lead times, North Pacific SST anomalies driven by ENSO may tend to be overestimated in models having an overly strong ENSO, as the models drift away from observation-based initial conditions and this bias sets in." And third, "the relative preponderance of low-frequency variability in the models suggests that climate forecasts may overestimate decadal to multidecadal variability in the North Pacific."

Kim *et al*. (2012) state "the Coupled Model Intercomparison Project Phase 5 (CMIP5) has devised an innovative experimental design to assess the predictability and prediction skill on decadal time scales of state-of-the-art climate models, in support of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report," citing Taylor *et al*. (2012). To date, however, they note decadal predictions from different CMIP5 models "have not been evaluated and compared using the same evaluation matrix," a problem they resolve with their study for some of the models. Kim *et al*. assessed the CMIP5 decadal hindcast-forecast simulations of seven state-of-the-art ocean-atmosphere coupled models for situations where "each decadal prediction consists of simulations over a 10-year period each of which are initialized every five years from climate states of 1960/1961 to 2005/2006."

The three U.S. researchers report "most of the models overestimate trends," in that they "predict less warming or even cooling in the earlier decades compared to observations and too much warming in recent decades." They also report "low prediction skill is found over the equatorial and North Pacific Ocean" and "the predictive skill for the Pacific Decadal Oscillation index is relatively low for the entire period." They conclude "the prediction of decadal climate variability against a background of global warming is one of the most important and challenging tasks in climate science."

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1.4.3 Intertropical Convergence Zone

It is well-known among scientists in the climate modeling community that GCMs erroneously produce a double Intertropical Convergence Zone (ITCZ) in the Central Pacific much more often than is typically observed. The ITCZ is a "belt" of low pressure that girdles the equatorial tropics and identifies the convergence of Earth's trade wind belts. Usually, a double ITCZ is observed in the Central Pacific during the Northern Hemisphere spring season only, and not during the rest of the year.

Flaws in the construction of the models, in their numerics and in their physics, are discussed often. But analyses using even erroneous models can sometimes be useful not only in learning where models are deficient but also in identifying where or how the observations need to be improved.

Liu *et al.* (2012) used the Community Climate System Model version 3 (CCSM3), which includes an atmospheric model, a land surface model, and a dynamic ocean model. The model was of intermediate resolution in the horizontal, the equivalent of 2.8 degrees latitude/longitude. There are 26 model layers in the atmosphere. The authors focused on the first one to two years of the model integration in order to locate the problems causing the double ITCZ over the tropics between 170° E and 150°W. The observed data used as input were archived at the Massachusetts Institute of Technology, and the cloud data were derived from the International Satellite Cloud Climatology Project.

Liu *et al.* learned warm biases in the sea surface temperatures developed within two years of the initial start-up, and these became substantial and similar to those of other studies after five simulation years. The CCSM model also produced a cold bias south of 10°S. The warm bias was present in all seasons. The effect of the warm and cold bias was to establish unrealistic temperature gradients, which in turn affected the winds and the latent heat flux (moisture) into the atmosphere.

The authors additionally found the warm bias was due to excessive solar radiation, at least at first, augmented by excess latent heating later. The root cause was less cloudiness in the model than was observed in the region. These biases induced errors in the ocean structure of the region studied, resulting in a modeled eastward current where a westward current exists in the observations. An experiment was then run by artificially increasing the cloudiness within the region and the problems described above were alleviated.

Liu *et al.* eventually traced the problem of insufficient cloudiness in the study region to low cloud liquid water path in the model (Figure 1.4.3.1), but "whether this is due to insufficient absorption of solar radiation in clouds, or insufficient cloud amount or aerosols, is not clear."

The goal of Liu *et al.*'s work was to determine how the CCSM model developed a double ITCZ in the Central Pacific. This double Central Pacific ITCZ appears to be a problem for many models. The appearance of a double ITCZ means a model fails to simulate tropical climate well and, given the interactions of this region with the mid-latitudes, these simulation problems would be felt in the model far from the study region.

Reference

Liu, H., Zhang, M., and Lin, W. 2012. An investigation of the initial development of the double-ITCZ warm SST biases in the CCSM. *Journal of Climate* **25**: 140–155.

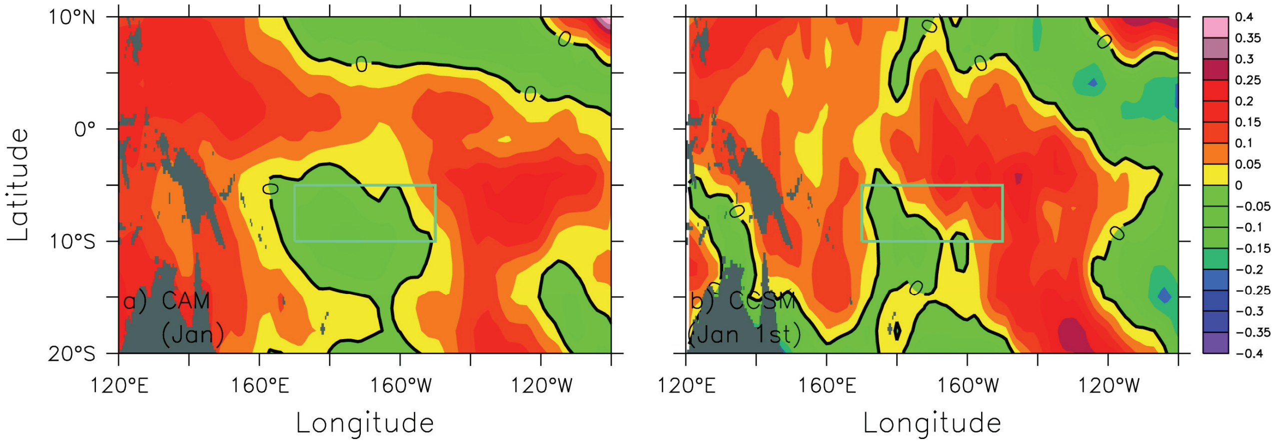

Figure 1.4.3.1. The differences in the total cloud amount between the model and observed cloudiness (%) for the first month of the (a) atmospheric model only, and (b) the full CCSM ensemble mean. The green box bounded by 170°E and 150°W and 5° to 10°S is the domain over which the authors studied the heat budgets. Reprinted with permission from Liu, H., Zhang, M., and Lin, W. 2012. An investigation of the initial development of the double-ITCZ warm SST biases in the CCSM. *Journal of Climate* **25**: 140–155.

1.4.4 South Pacific Convergence Zone

The South Pacific Convergence Zone (SPCZ) is a permanent feature in the general circulation that stretches southeastward from the equatorial region of the west Pacific into the central mid-latitude Pacific near Polynesia. This band of precipitation has drawn the interest of the climatological community because it behaves like the ITCZ in the tropics but is driven by jet-stream dynamics in the mid-latitudes. Like the ITCZ, it is a locus for the occurrence of precipitation in the regions it impacts.

Previous research has demonstrated the observed behavior and location of the SPCZ varies in relation to the phase of El Niño. During an El Niño year, the SPCZ is located closer to the equator and can be oriented in a more zonal fashion, and these changes are more robust during stronger El Niño events. At such times, Indonesia, Australia, and southwest Pacific nations are subjected to reduced rainfall, which of course affects the regional ecology.

In a letter to *Nature,* Cai *et al.* (2012) compared the larger-scale components of the SPCZ rainfall anomalies derived from observations during the period 1979–2008 to rainfall anomalies generated by 17 CMIP3 general circulation model simulations covering the period 1891–2000. These simulations included known natural and anthropogenic forcings. The team of researchers then generated 90-year simulations using the A2 greenhouse emission scenarios, which assume business as usual or accelerating greenhouse gas emissions. Cai *et al.* also applied the same strategy with CMIP5 models under a scenario that levels out at 850 ppm during 200 years assuming 1 percent increases per year until stabilization. This is similar to the A2 scenario.

The work of Cai *et al*. revealed stronger SPCZ events will occur with greater frequency in the future under the increased greenhouse gas scenarios in both models (doubled in CMIP3 and tripled in CMIP5). This implies increased frequency of drought for the regions of the southwest Pacific. Both models also implied stronger El Niño events occur more frequently in the future scenario, but not as frequently as the increased SPCZ occurrences. Curiously, these results also imply SPCZ behavior decouples from that of El Niño.

The conclusion that stronger SPCZ events will occur in the future was based on a greenhouse gas emission scenario considered quite extreme. Additionally, although there may be a physical reason for future decoupling of the relationship between SPCZ strength and location and the strength of El Niño, it should be noted the modeled SPCZ orientation seems to be more zonal than observed even before the future scenarios are generated (compare Figure 1.4.4.1 and Figure 1.4.4.2).

The authors admit to some uncertainty in the observed SPCZ position: "Although the simulated frequency in the control period is comparable to the observed frequency, the latter is based on observations over some three decades and may carry a large uncertainty." Like many modeling studies, the outcome of Cai *et al.* is properly understood as nothing more than a scenario based on a specific set

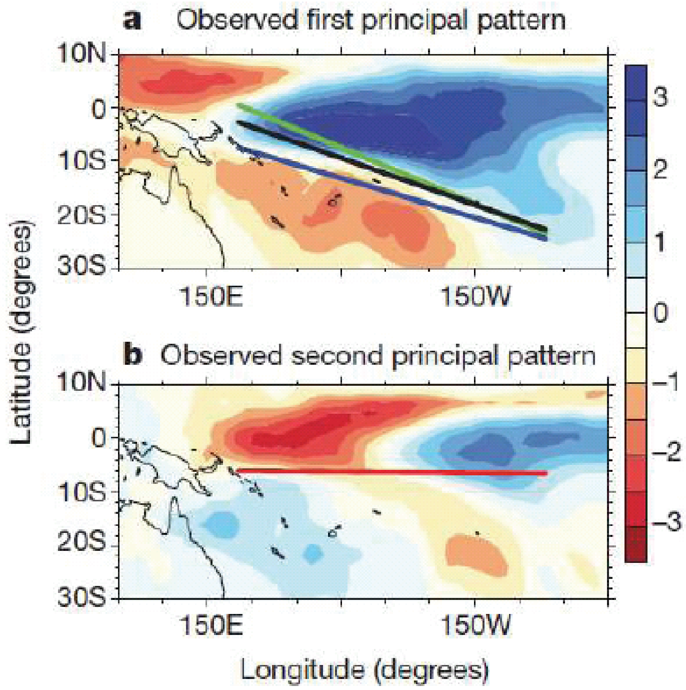

Figure 1.4.4.1. The variability of observed rainfall for the (a) spatial pattern of the largest-scale component of the observed precipitation anomalies that was filtered out, and (b) second-largest component of the observed anomalies extracted from the satellite-era rainfall anomaly data (mm d^{-1}) (Global Precipitation Climatology Project version 225) focusing on the western South Pacific during the austral summer (December to February). The first (second) principal patterns account for 47% (16%) of the total variance. The SPCZ position (max rainfall greater than 6mm d^{-1}) for El Niño (green line), La Niña (blue line), and neutral (black line) states is superimposed in a, and the position for zonal SPCZ events (red line) in b. Cold (warm) contours indicate increased (decreased) rainfall per one standard deviation (s.d.) change. Reprinted with permission from Cai, W., Langaigne, M., Borlace, S., Collins, M., Cowan, T., McPhadden, M.J., Timmermann, A., Power, S., Brown, J., Menkes, C., Ngari, A., Vincent, E.M. and Widlansky, M.J. 2012. More extreme swings of the South Pacific Convergence Zone due to greenhouse warming. *Nature* **488**: 365-369, Figure 1.

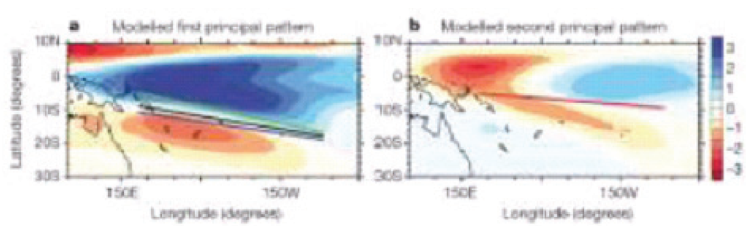

Figure 1.4.4.2. As in Figure 1.4.4.1, except for the CMIP model runs.

of assumptions, with limitations on the ability to capture the phenomenon in question precisely. Their results have only limited scientific value.

Reference

Cai, W., Langaigne, M., Borlace, S., Collins, M., Cowan, T., McPhadden, M.J., Timmermann, A., Power, S., Brown, J., Menkes, C., Ngari, A., Vincent, E.M. and Widlansky, M.J. 2012. More extreme swings of the South Pacific Convergence Zone due to greenhouse warming. *Nature* **488**: 365-369.

1.4.5 Hadley Circulation

The Hadley Circulation, or Hadley Cell, is an important general circulation of Earth's climate. It is named for Sir George Hadley, who first attempted to describe Earth's circulation in a general way. Warm equatorial air rises, while cold polar air sinks, and a hemisphere-wide circulation loop is formed. Hadley was partly correct but failed to account for the Coriolis Effect, which was discovered by later researchers.

The Hadley Cell emerges from an analysis of the tropics when atmospheric motions are averaged on the time scale of a month or more. In a classical view of this circulation, there are upward motions and low pressure at the equator (mainly associated with deep convection clouds), poleward moving air aloft, downward motion around 30^{o} latitude, associated with the subtropical highs, and equatorward moving air (the trade winds) in the lower atmosphere. Studies have suggested the latitudinal extent of the Hadley Cell may have widened in the past few decades.

Levine and Schneider (2011) used a crude atmospheric general circulation model to examine the strength and span of the HC over a wide range of climates. They performed this study because some studies show the HC strengthens, while others show it weakens, in response to global warming. As Levine and Schneider report in describing the rationale behind their study, "despite a large body of observations and numerous studies with GCMs, it remains unclear how the width and strength of the

Hadley Circulation are controlled."

Levine and Schneider used an idealized radiative transfer scheme and moist thermodynamics. The model was based on one used at the Geophysical Fluid Dynamics Laboratory, a model with relatively coarse resolution (about 2.8° latitude/longitude) and 30 levels in the vertical. The planet "surface" was water-covered only. The oceans included simple dynamics for heat transport (which was turned "on" and "off"), and the model was driven with the annual mean insolation, thus there was no diurnal or annual cycle. In this way the authors could isolate two variables, the strength of the HC versus global temperature (controlled by the absorption of longwave radiation only).

The authors established a baseline climate for their aqua-planet and ran the model with and without ocean dynamics. The results were more realistic with the ocean dynamics. Then, the longwave absorption, a function of latitude and pressure (height), was varied by a constant amount between 0.2 and 6.0 times the control value. This produced a global climate with planetary temperatures varying between 260 K and 315 K (roughly -13°C to 42°C; today it is roughly 15°C). The equator-to-pole temperature differences decreased linearly with increasing temperature.

In their simulations, the strength of the Hadley Cell did not change linearly (Figure 1.4.5.1) but rather was more parabolic in shape, which makes the situation more complicated. The Hadley Circulation in their model was weaker in both very cold and very warm climates. Also, Figure 1.4.5.1 implies ocean dynamics become less important in determining the strength of the Hadley Circulation as climate warms. This is true because the equator-to-pole temperature difference becomes negligible. In colder climates, the weakening is the result of a more geostrophic, or zonal, atmospheric flow. A more zonal flow would imply less wave action in the jet stream, which means less energy exchange. Today's climate is roughly at the maximum in the ocean dynamics curve.

The behavior of atmospheric systems can be complicated even when there are few variables. This has led to studies whose findings initially seem to be contradictory, for example, in a warmer climate. The behavior of changes in the strength of the Hadley Circulation is nonlinear even in the simple model of Levine and Schneider (2011). Adding complexity to the model would make interpretation of the output more difficult. This demonstrates the importance of understanding the fundamental behavior of phenomena like the Hadley Circulation.

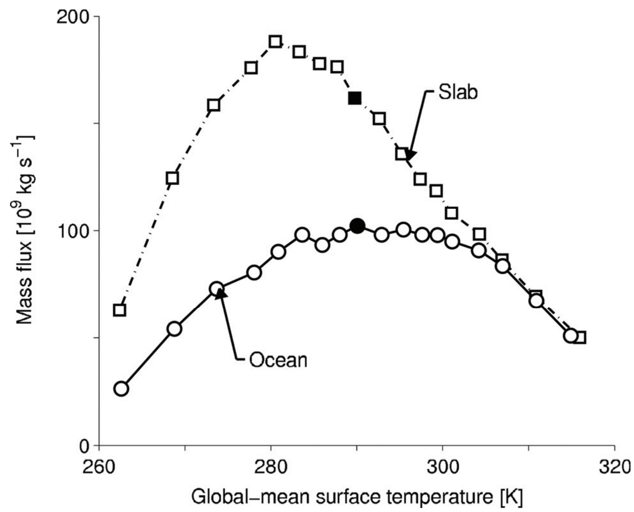

Figure 1.4.5.1. The strength of HC in simulations with (solid, circles) and without (dashed, squares) ocean dynamics. Shown is the absolute value of the mass flux at the latitude of its maximum and at the level σ_c = 0.7, averaged for both hemispheres. The filled symbols are the reference simulations. Reprinted with permission from Levine, X.J. and Schneider, T. 2011. Response of the Hadley Circulation to Climate Change in an Aquaplanet GCM Coupled to a Simple Representation of Ocean Heat Transport. *Journal of the Atmospheric Sciences* **68**: 769–783, Figure 4.

Reference

Levine, X.J. and Schneider, T. 2011. Response of the Hadley Circulation to Climate Change in an Aquaplanet GCM Coupled to a Simple Representation of Ocean Heat Transport. *Journal of the Atmospheric Sciences* **68**: 769–783.

1.4.6 The Madden-Julian Oscillation

The Madden-Julian Oscillation (MJO) is a tropical phenomenon discovered in the early 1970s; it is a 30- to 70-day oscillation in the west-to-east component of the tropical winds between 20°N and 20°S. The MJO has been detected in tropical convection and precipitation, both of which are enhanced in the "trough" phase. Although the dynamics that drive the MJO are not fully understood, it is known to interact with larger-scale phenomena such as tropical cyclones, monsoons, and El Niño and the Southern Oscillation (ENSO), as well as with the general circulation itself. The MJO has been linked to mid-latitude circulations, especially during the warm season and over North America.

General circulation models have had difficulty in representing the MJO and its impact on larger-scale phenomena could not be captured, due primarily to the inadequate representation of the associated convection. This is but one factor that causes GCMs fail, to a certain degree, in representing the large scale correctly.

Subramanian *et al.* (2011) used the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4) model to examine its ability to capture the MJO, which included an upgrade to the convective parameterization scheme. This upgrade "improves the correlation between intraseasonal convective heating and intraseasonal temperature, which is critical for the buildup of available potential energy."

The authors used a 500-year simulation of the CCSM4 using pre-1850 conditions as a control run. They then extracted two ten-year periods from these data, each representing the strongest and weakest ENSO variability in the 500-year period. They compared this data set to observed Outgoing Longwave Radiation (OLR), a commonly used proxy for convection, as well as tropical precipitation and zonal winds at 850 and 200 hPa taken from the NCAR/NCEP reanalyses. Lastly, the authors examined the relationship between the MJO and such general circulation features as ENSO and the monsoons in both the model and observations.

Subramanian *et al.* found the CCSM4 produced a feature that propagated eastward in the "intraseasonal zonal winds and OLR in the tropical Indian and Pacific Oceans that are generally consistent with MJO characteristics." Thus the model performed well overall in capturing the MJO (Figure 1.4.6.1), but there were still some differences. Whereas the observations produced a strong (weaker) wave number one (two and three) in the data, the modeled MJO showed more coherency among the wave numbers one-three. This suggests stronger Kelvin wave activity at the higher wave numbers in the

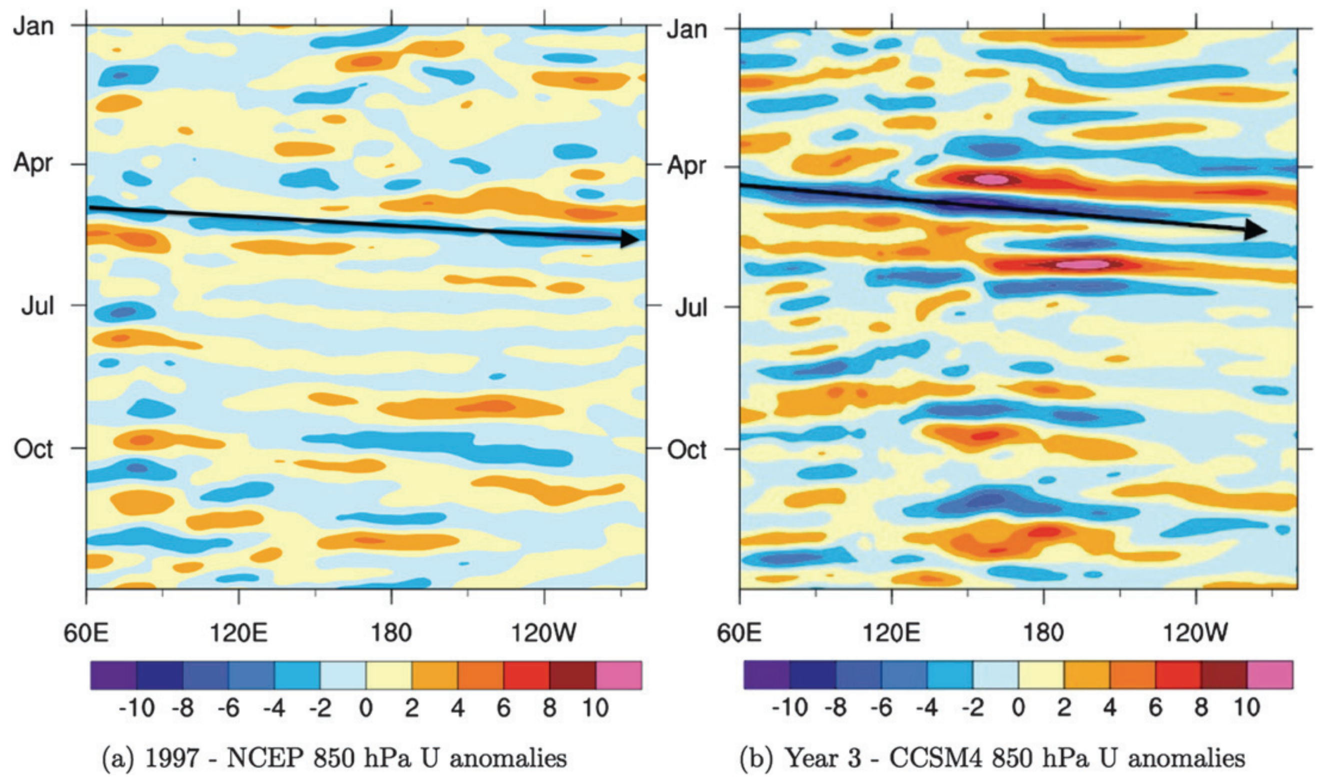

Figure 1.4.6.1. A Hovemöller plot of the zonal winds at 850 hPa filtered to retain the 20-100 day signal for the (a) NCAR/NCEP reanalyses from 1997 and (b) year 3 of the CCSM4 run. The arrow is added to demonstrate the eastward propagation of weaker 850 hPa winds which represents the MJO. Reprinted with permission from Subramanian, A.C., Jochum, M., Miller, A.J., Murtugudde, R., Neale, R.B., and Waliser, D.E. 2011. The Madden-Julian Oscillation in CCSM4. *Journal of Climate* **24**: 6261–6282.

model.

When examining the relationship of the MJO to other phenomenon, the authors found MJO activity was enhanced (weaker) during El Niño (La Niña) years. Also, the MJO occurred more often in the Indian Ocean monsoon region during negative shear regimes (shear defined by the zonal wind at 850 hPa minus the meridional [north-south] wind at 200 hPa). The MJO occurred more often when the Hadley Circulation in the tropics was weaker as well. These phenomena are interrelated, and thus the authors state, the "MJO could thereby be simultaneously affected in multiple ways when these type of large-scale climate mode interactions occur and possibly feed back onto the entire coupled system."

The outcome of this work demonstrates how difficult it is to represent the current state of the climate, as well as the interannual variability in the climate system. Models continue to improve through the increase in resolution and improvement in sub-grid-scale physical processes. Even though this model showed a distinct improvement in representing the MJO, there were still some differences between the model and the observed MJO. The MJO represents only one critical link between the small-scale atmospheric motions and the general circulation.

Reference

Subramanian, A.C., Jochum, M., Miller, A.J., Murtugudde, R., Neale, R.B., and Waliser, D.E. 2011. The Madden-Julian Oscillation in CCSM4. *Journal of Climate* **24**: 6261–6282.

1.4.7 Atmospheric Blocking

A phenomenon not often discussed in climate change studies is atmospheric blocking, which develops when there is a stationary ridge of high pressure in the mid-latitude jet stream. This phenomenon is typically associated with unusually warm and dry weather in areas where these high-pressure ridges form, and cooler or wetter conditions upstream and downstream of where they occur. The Western European heat wave of 2003, the extreme heat in Russia in 2010 and the downstream flooding in Pakistan, and the cold temperatures over most of North America and Europe during December 2010 are recent examples of blocking and its impact on regional weather.

The first investigation into blocking characteristics in an increased CO_2 and warmer environment was performed by Lupo *et al.* (1997) using the Community Climate Model version 1 (CCM1). The results of their blocking climatology using CCM1 were comparable to those of Bates and Meehl (1986), who used CCM0B. Both of these efforts found significant differences from observations: in the Atlantic there were fewer events, and in the Northern Hemisphere there were more summer season events. Model blocking also was weaker and less persistent than observations.

When present-day CO_2 concentrations were doubled, the researchers generally found blocking anticyclones were more persistent but weaker than their counterparts in the control experiment. All other characteristics of the overall sample—such as frequency of occurrence, size, preferred genesis locations, and annual variations in size and intensity—were generally similar to the control experiment. The regional and seasonal analysis identified significant differences between the two climatologies. Perhaps the most striking difference was the threefold or more increase in continental region block occurrences and total block days, due to the appearance of the observed western Asian Continental maximum in the double CO_2 run. There also was an increase in blocking frequency over the North American continent compared to the control and observations.

A newer investigation into the blocking phenomenon by Kreienkamp *et al*. (2010) used National Centers for Atmospheric Research re-analyses to examine the occurrence of blocking events over Europe since the 1950s, using a well-known blocking index (Tibaldi and Molteni, 1990). Kreienkamp *et al*. employed the atmospheric general circulation model (ECHAM) used by the IPCC in an effort to determine how well the model simulated such blocking. They also examined two climate warming scenarios (A1B and B1) for the twenty-first century in order to infer whether blocking will become more or less common in based on model projections.

With respect to the re-analysis data, Kreienkamp *et al*. found little evidence of a statistically significant trend over the period 1951–2007 apart from a weak decrease in the European region; this decrease suggests extreme weather events caused by blocking events probably have also declined. With respect to model simulations, they found the models showed little change in the frequency, seasonality, or interannual variability of blocking for the Atlantic/ European region as a whole but a significant decrease in Central European region frequency.

Another study of blocking by Scaife *et al.* (2010) set out to determine whether model error in the large- or small-scale processes is responsible for the underestimate of blocking. They first produced a blocking climatology using the Hadley Centre Global Environmental Model (HadGEM), an atmospheric general circulation model. They used a version of the zonal index to diagnose blocking (Berrisford *et al*., 2007) and observed data archived at the European Centre for Medium Range Forecasting (ERA-40 re-analyses) for comparison (Figure 1.4.7.1). Then the authors extended the study to 18 other simulations produced using various GCMs for the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report*.

Since the zonal index is generally used to represent blocking, the authors separated the zonal mass gradient produced by the HadGEM model and in the observed data into a climate mean (large-scale) component versus that of the time-varying portion (small-scale). When they replaced the large-scale model data with the observed (keeping the small-scale model part), they showed the blocking frequency was reproduced more faithfully. The same result was found in the IPCC simulations and by Lupo *et al*. (1997).

Scaife *et al*. state, "commonly applied statistics based on absolute measures (such as the reversal of the geopotential height or potential vorticity gradients) show large errors in current climate models, but these are directly attributable to a large degree to errors in the main state." Scaife *et al.* also show improvements in the large-scale model performance can greatly improve the capability of the model to reproduce blocking characteristics.

The latest study by Mokhov *et al*. (2013) for the projection of blocking in the twenty-first century using the Institut Pierre Simon Laplace Climate Model versions 4 (IPSL-CM4) GCM and the SRES-A1B and SRES-A2 scenarios showed a slight increase in the number and persistence of blocking events over the Atlantic-Eurasian region and no change in the interannual or interdecadal variability. These results are similar to the other studies examined here.

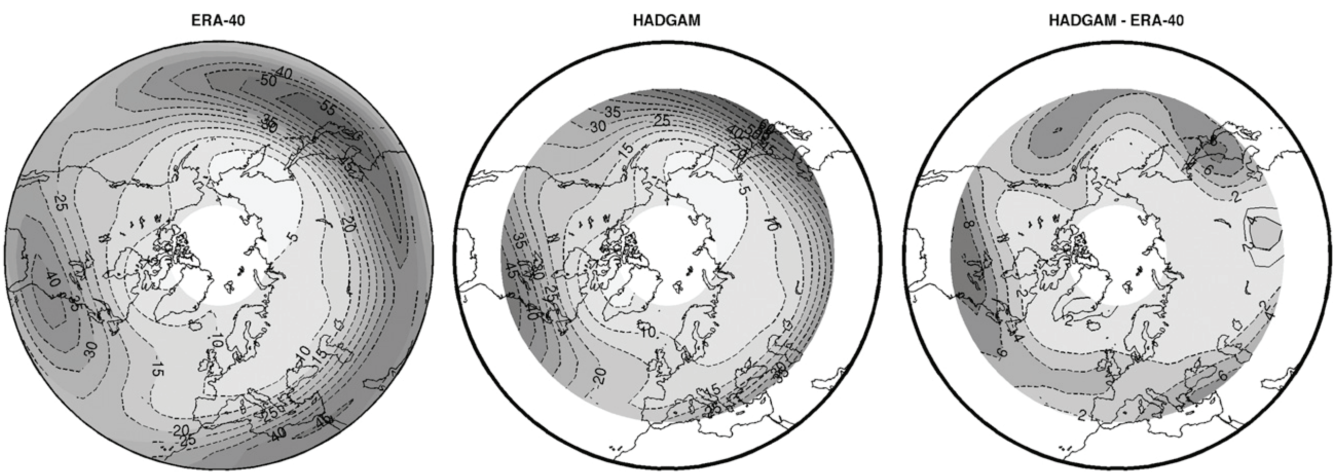

Figure 1.4.7.1. The climatological frequency of the winter season blocking using the Berrisford et al (2007) index (not blocking frequency). Shown are the (left) ERA-40 reanalyses, (middle) HadGEM Model, and (right) the model error. The hemispheric nature of the model error shows that it is present at all longitudes. Units are K^{-1}. Reprinted with permission from Scaife, A.A., Wollings, T., Knight, J., Martin G., and Hinton, T. 2010. Atmospheric blocking and mean biases in climate models. *Journal of Climate* **23**: 6143–6152.

Although caution should be emphasized in interpreting the model projections, the findings of these studies are good news, for they suggest the number of heat waves and/or cold waves that can be attributed to atmospheric blocking will not increase for the Atlantic/European region in the twenty-first century. In fact, the model output suggests fewer of these occurrences and/or a shorter duration of such events (e.g., Kreiencamp *et al*., 2010).

Studies by Liu *et al.* (2012) and Jaiser *et al.* (2012) find an increase in observed blocking since 1995 consistent with that found by Mokhov *et al.* (2013), but rather than linking this to internal variability, including changes in the phases of multidecadal oscillations, they attribute the change to anthropogenic climate warming. A paper by Hakkinen *et al.* (2011) takes a more measured approach, stating, "the warm-ocean/cold-land anomaly pattern has been linked to a dynamical environment favorable for blocking" and "the possibility of coupled interaction of atmosphere with [Atlantic Multidecadal Variability] seems likely, given the long-period variability of blocking reported here and in the even longer paleoclimate time series." The latter position is more consistent with the studies reviewed here.

Two studies provide additional evidence for the lack of trends in Northern Hemisphere blocking patterns. Screen and Simmonds (2013) studied "observed changes (1979–2011) in atmospheric planetary-wave amplitude over northern mid-latitudes, which have been proposed as a possible mechanism linking Arctic Amplification (AA) and mid-latitude weather extremes." However, they found few if any large or statistically significant changes, instead noting "Statistically significant changes in either metric are limited to few seasons, wavelengths and longitudinal sectors" and "Even ignoring the lack of significance, there is no clear tendency towards larger or smaller [wave amplitude] (60% negative trends and 40% positive trends). Nor is there a general tendency towards longer or shorter wavelengths (i.e., longer wavelengths are not increasing in zonal amplitude at the expense of shorter wavelengths), or vice versa."

Most recently, Barnes (2013) investigated "trends in the meridional extent of atmospheric waves over North America and the North Atlantic … in three reanalyses." Barnes's work "demonstrated that previously reported positive trends are an artifact of the methodology" and further "the mechanism put forth by previous studies (e.g. Francis and Vavrus [2012]; Liu *et al*. [2012]), that amplified polar warming has led to the increased occurrence of slow-moving weather patterns and blocking episodes, is unsupported by the observations."

One of the criticisms of model projections used to produce climate change scenarios for the twenty-first century is that the models still have difficulty reproducing various aspects of the observed climate, including even the large-scale features (Scaife *et al*., 2010). Blocking is one of these phenomena, and it is often used as a surrogate for the occurrence of extreme conditions (heat waves, cold waves). If the models cannot adequately represent blocking in the current climate, results regarding the occurrence of extreme events in future climate change scenarios must be examined with caution.

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1.4.8 Tropical Cyclones

Tropical cyclones (TCs) form and are maintained by the cooperative forcing between the atmosphere and oceans. Warm tropical waters (sea surface temperatures or SSTs) are the energy source needed to generate and maintain them, but favorable atmospheric conditions (e.g., low wind shear) are just as critical. These atmospheric conditions can be correlated to warm tropical SSTs. But warmer SSTs by themselves do not always portend more TCs. Some general circulation model studies have projected there will be as much as a 200 percent increase in TC occurrence in a warmer world, while other GCM studies suggest such a world will bring fewer TCs.

Villarini *et al.* (2011) attempted to explain why there is a large spread in the projection of TC occurrences that may occur in the future. They used a statistical model trained using a 131-year record of North Atlantic TC occurrences, a Poisson regression type model that generated land-falling or Atlantic TC frequencies as a function of Atlantic region and/or tropical mean SSTs. The SSTs included variability related to the North Atlantic Oscillation (interdecadal) and the Southern Oscillation Index (interannual). The authors compared the statistical model results with those produced by dynamic GCMs and statistical-dynamic models for the Intergovernmental Panel on Climate Change (IPCC). In order for the comparisons to be more faithful, the authors used the SST time series in the statistical model that each particular IPCC model scenario used.

When both the Atlantic region and tropical mean SSTs were used, there was good agreement between the results of the statistical model and that of the dynamic models (Figure 1.4.8.1). Tropical SSTs elsewhere can affect Atlantic TC occurrence via variations in the jet stream. The authors note, "the agreement between the statistical and dynamical models is rather remarkable, considering the simplicity of the statistical model." They also state "it appears that the differences among the published results can be largely reduced to differences in the climate model projections of tropical Atlantic SST changes relative to the global tropics used by the studies."

When Villarini *et al.* used Atlantic SST alone, there was little agreement between the statistical and dynamic models, with the statistical models showing large biases in TC frequency. The dynamic models did not show this bias, supporting the notion that SSTs alone cannot explain variations in TC occurrence. There were also mixed signals produced by the IPCC models with regard to landfalling TCs, half showing a statistically significant increase and the other half showing a significant decrease. The authors suggest that in order to reduce the uncertainty in future TC occurrence, the uncertainty in tropical Atlantic and tropical mean SSTs and their difference should be reduced.

With respect to claims that increases in TC frequency and strength will occur as a result of anthropogenic global warming, and coastal areas will be more vulnerable to destruction, the authors state, "the results do not support the notion of large (~200%) increases in tropical storm frequency in the North Atlantic Basin over the twenty-first century in response to increasing greenhouse gasses (GHGs)." Instead they found it is more likely TC frequency may change by +/- 40% by the late twenty-first century and this "is consistent with both the observed record and with the range of projections of SST patterns."

Models also have had difficulty replicating the dynamic structure of tropical cyclones. This is partially due to the vertical exchanges being dominated by deep convection, which is on a scale below the resolution of the grid. Another contributing factor is that the models' resolution is insufficient to define the relatively small scale circulation, especially the eye wall where the circulation is most intense. In addition, the paucity of observations means the factors triggering tropical cyclone development are poorly known. Early atmospheric general circulation models (AGCMs) had horizontal resolutions the equivalent of approximately 450 km. In such a model, resolving individual storm events was impossible, and these could only be inferred from the aggregate statistical properties of quantities such as momentum or temperature flux.

Manganello *et al.* (2012) employed the European Centre for Medium-Range Weather Forecasts (ECMWF) IFS model to examine the climatology of TCs by identifying individual events. This model is the recent version of the ECMWF GCM and includes the latest physical packages for cloud formation (i.e., prognostic equations for cloud water), land surface processes and hydrology, and improved convective adjustment schemes. The latter provided for a better

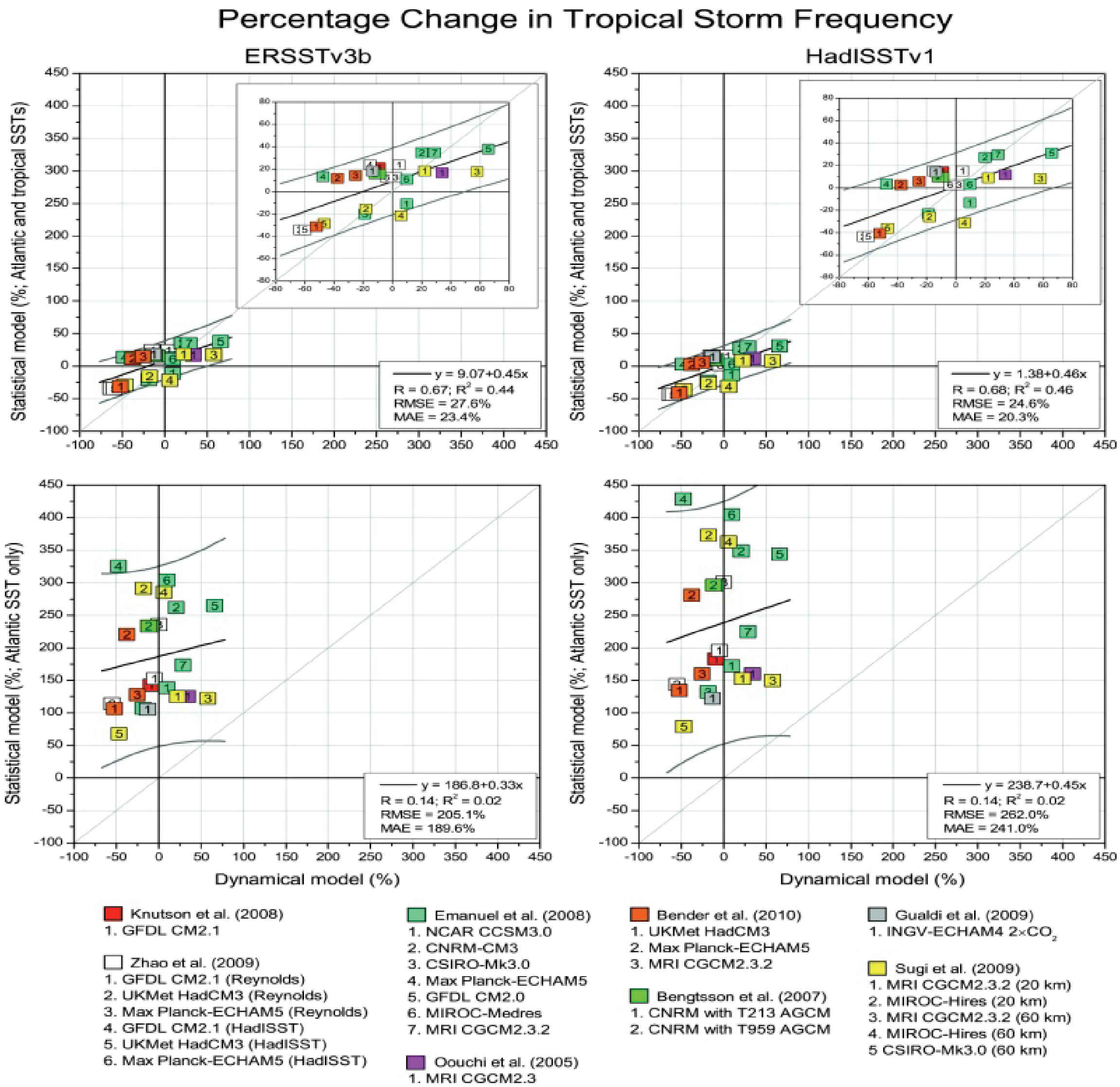

Figure 1.4.8.1. A comparison of the fractional TC count changes between the statistical model and IPCC dynamic models. The top (bottom) figures shows the use of Atlantic region and tropical (Atlantic region only) SSTs. The left (right) side panels were formulated using the NOAA ERSSTv3b (HadISSTv1) dataset. The gray lines define the 90% prediction interval for the linear regression model. Reprinted with permission from Villarini, G., Vecci, G.A., Knutson, T.R., Zhao, M., and Smith, J.A. 2011. North Atlantic tropical storm frequency response to anthropogenic forcing: Projections and sources of uncertainty. *Journal of Climate* **24**: 3224–3238.

representation of tropical weather and year-to-year variations in tropical climate.

The model was run for "Project Athena" (Jung *et al.*, 2012) with resolutions at 125 km, 39 km, 16 km (the current resolution of a weather forecast model), and 10 km; for all there were 91 levels in the vertical. The model also was run for each year from 1960 to 2008 for the larger resolutions, and for 1989–2008 for the 10 km run. To keep the data storage manageable, the authors used data for May through November in the Northern Hemisphere (NH) for 1990–2008. The authors also controlled the data to make sure storms identified were indeed TCs, such as requiring a warm core, meaning the center is warmer than the surrounding environment.

Manganello *et al.* found over the entire NH, the 39 km run produced the most realistic count for TCs; the higher resolution model produced too many TCs. Within each basin (e.g., Atlantic) or sub-basin (Northwest Pacific), however, the higher resolutions occasionally produced the best results. One problem for models is tropical cyclogenesis tends to be too weak, and it was a problem here in spite of better resolution. In a related matter, the model produced TCs that were weaker than observed in terms of wind speed but comparable in terms of central pressure (Figure 1.4.8.2). Finally, the higher model resolution runs did better in capturing ENSO variability of TCs. ENSO is well-known to have a large influence on the interannual variation of TC occurrence and intensity.

Manganello *et al.* note, "as computing power continues to grow, it is becoming increasingly possible to model the global climate at horizontal resolutions presently used in short-term weather prediction." Although hindcasts with improved resolution and physics still have difficulty representing observations to a high degree, the models are able to reasonably reproduce the number of events, and even produced structures that look like observed TCs (Figure 1.4.8.3), thus, passing the test. These kinds of advances represent progress and should make future computer scenarios for climate more reasonable and useful.

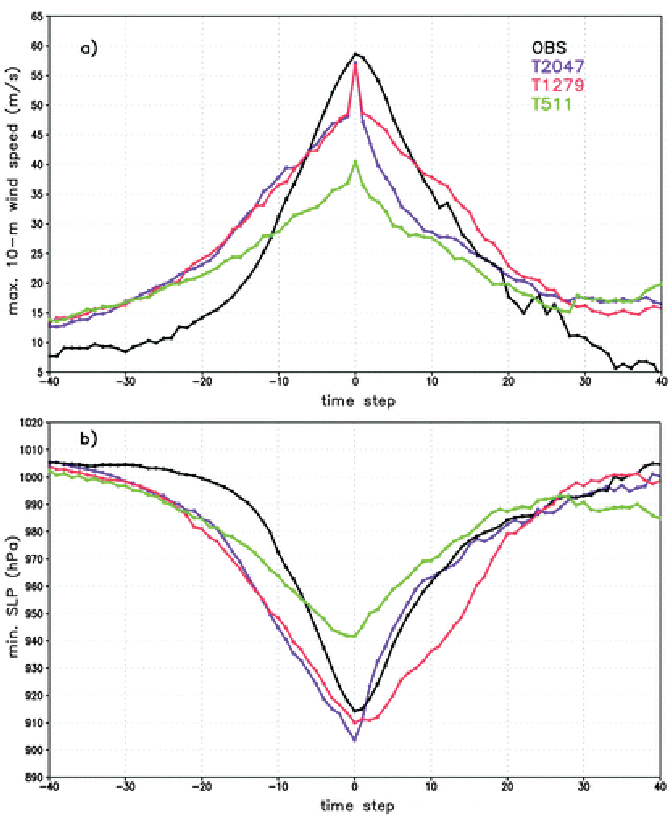

Figure 1.4.8.2. Life cycle composite of the (a) maximum 10-m wind speed and (b) minimum SLP for the 25 most intense typhoons, in terms of the maximum 10-m wind speed, over the northwest Pacific for observed data (black), the 10-km (purple), the 16-km (red), and 39-km (green) runs during MJJASON of 1990–2008. The time step is in 6-h increments. Reprinted with permission from Manganello, J.V., Hodges, K.I., Kinter III, J.L., Cash, B.A., Marx, L., Jung, T., Achuthavarier, D., Adams, J.M., Altshuller, E.L., Huang, B., Jin, E.K., Stan, C., Towers, P., and Wedi, N. 2012. Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather-resolving climate modeling. *Journal of Climate* **25**: 3867–3892, Figure 9.

The studies of Dare and McBride (2011) and Park *et al.* (2011) have demonstrated tropical cyclones (TCs) can significantly cool the surface waters in their wakes for periods of several days to weeks. Manucharyan *et al*. (2011) write, "TC-induced ocean mixing can have global climate impacts as well, including changes in poleward heat transport, ocean circulation, and thermal structure." They note, however, that "in several previous modeling studies devoted to this problem, the TC mixing was treated as a permanent (constant in time) source of additional vertical diffusion in the upper ocean." They thus explore the "highly intermittent character of the mixing" and what it portends for global climate, using a global ocean-atmosphere coupled model and a simple heat transfer model of the upper ocean.

The three Yale University researchers mimicked the effects of TCs using several representative cases of time-dependent mixing that yield the same annual mean values of vertical diffusivity, conforming with the studies of Jansen and Ferrari (2009) and Fedorov *et al*. (2010), wherein spatially uniform (but varying in time) mixing is imposed on zonal bands in the upper ocean.

Manucharyan *et al*. observed "a weak surface cooling at the location of the mixing (~0.3°C), a strong warming of the equatorial cold tongue (~2°C), and a moderate warming in middle to high latitudes (0.5°C-1°C)," together with "a deepening of the tropical thermocline with subsurface temperature anomalies extending to 500 m [depth]." They say "additional mixing leads to an enhanced oceanic heat transport from the regions of increased mixing toward high latitudes and the equatorial region."

"Ultimately," the researchers state, "simulations with TC-resolving climate models will be necessary to fully understand the role of tropical cyclones in climate," for "the current generation of GCMs are only slowly approaching this limit and are still unable to reproduce many characteristics of the observed hurricanes, especially of the strongest storms critical for the ocean mixing (e.g., Gualdi *et al*., 2008; Scoccimarro *et al*., 2011)."

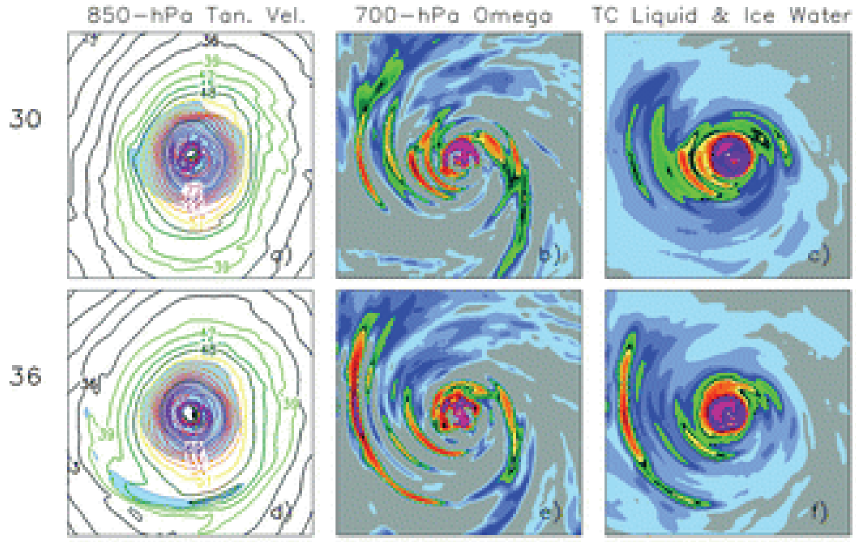

Figure 1.4.8.3. (Left panel) 850-hPa tangential velocity (m s^{-1}), (middle) 700-hPa omega (Pa s^{-1}), and (right) TCLIW (kg m^{-2}) for 30 and 36 hours after onset as shown on the left for an intense TC (10-km resolution). Radius is 3.5° from the storm center. Blue shading on the left roughly delineates the regions where the local wind maxima occur. Adapted from Manganello, J.V., Hodges, K.I., Kinter III, J.L., Cash, B.A., Marx, L., Jung, T., Achuthavarier, D., Adams, J.M., Altshuller, E.L., Huang, B., Jin, E.K., Stan, C., Towers, P., and Wedi, N. 2012. Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather-resolving climate modeling. *Journal of Climate* **25**: 3867–3892, Figure 12.

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1.4.9 Storm Tracks and Jet Streams

The climate of Earth's atmosphere is largely driven by forcing from the underlying surface, of which 71 percent is covered by the oceans. Thus the oceans and mountains are important in simulating storm tracks, and any simulations of present or future climate must be able to represent the land surface topography and the world oceans in a realistic way if the models are to be useful.

Storm tracks (Figure 1.4.9.1) are the climatological "signature" representing the frequency and strength of the regular passage of cyclonic disturbances. These disturbances are generally responsible for bringing weather that can be a minor nuisance on a typical day, such as rain or snow showers, or as severe weather that can cause loss of life and property. These low pressure systems are also a significant mechanism for the poleward transport of heat, momentum, and water vapor out of the tropics. These actions are necessary for maintaining the structure of Earth's current general circulation and climate.

Natural variations, as well as global or regional climate change, can induce changes in the storm tracks. As noted by Wilson *et al.* (2010), "as the climate changes, the ocean dynamics will change, but the land and mountains remain unchanged over millennia. Therefore in order to understand how the shape of the storm tracks will evolve, it is crucial to understand the relative impact of ocean dynamics and orography, as well as their interactions."

Four model worlds were constructed by Wilson *et al.* using a coupled ocean-atmosphere general circulation model. A model control run was performed with realistic topography and a fully dynamic ocean. Then, a typical modeling strategy was used to produce three other runs. This strategy involved using extreme and unrealistic parameterizations in order to isolate the impact of certain factors. A scenario was developed in which all land topography was leveled to 1 meter in height and the ocean was a 30-meter "slab" that does not move; a second scenario added mountains; and a third scenario was created without mountains but containing a fully dynamic ocean.

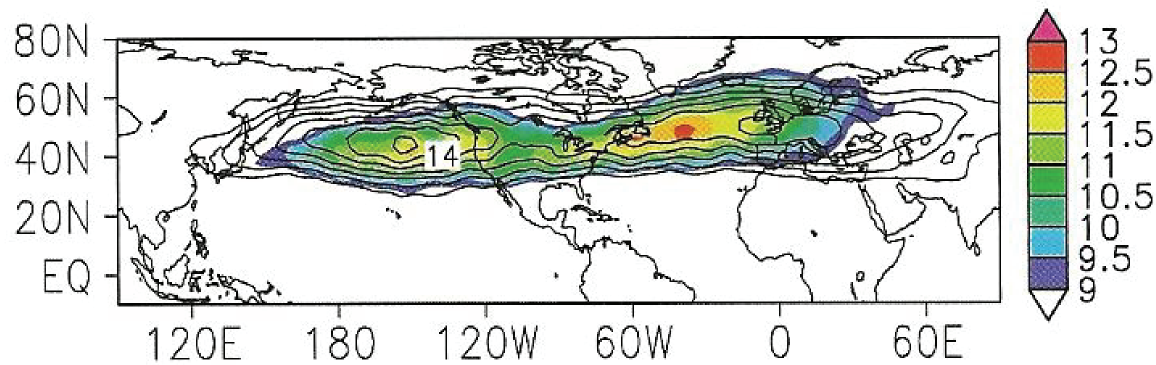

Figure 1.4.9.1. The mean winter Northern Hemisphere storm tracks from the European Center's observational reanalyses (colors), and the atmospheric general circulation model used in the Wilson et al. (2010) study (contours). The storm tracks were derived from the cyclone scale filtered upper air (250 hPa) kinetic energy. Reprinted with permission from Wilson, C., Sinha, B., and Williams, R.G. 2010. The shaping of storm tracks by mountains and ocean dynamics. *Weather* **65**: 320–323.

From the results of the model runs, Wilson *et al.* showed storm tracks are inherent in our atmosphere, as these features were found in the model run even without mountains and topography. In the model runs that included a dynamic ocean, the effect was to push the storm tracks poleward. The impact of the mountains was to reduce storm activity on their leeward side. The two combined features resulted in distinct Atlantic and Pacific storm tracks rather than just one long track in the Northern Hemisphere.

Changes in climate may also alter the storm tracks through changes in the frequency and intensity of the cyclones that comprise them. This would have an impact on the frequency and intensity of related phenomena such as blocking anticyclones. Blocking anticyclones are implicated in contributing to the European and Russian heat waves of 2003 and 2010, respectively. Such events also are implicated in severe winter cold across all continents. Thus, in order to discuss possible future scenarios for the climate or even the occurrence and severity of extreme events, any models used to generate these features must include interactive ocean dynamics.

And as Wilson *et al.* pointed out, "increased resolution is needed in coupled climate models to adequately address the role of ocean dynamics."

In examining the strength of storms, anthropogenic global warming (AGW) supporters have argued for decades that an increase in CO_2 will bring warmer temperatures and stronger and more destructive storm, including more hurricanes, tornadoes, and mid-latitude cyclones. Recently, they have argued the warmer temperatures will strengthen the water cycle, making these storms even stronger. Models have not been helpful in settling this argument, as some models imply storminess will decrease while others imply the opposite. In addition, empirical observations, which will be discussed in detail in Chapter 7 of this volume, do not support such projections.

The strength of the general circulation is controlled by two main factors. One is the equator-to-pole temperature difference (gradient) and the other is atmospheric stability. These ultimately drive the general circulation and give rise to the jet streams. In the mid-latitudes, where the gradient is strong, storms arise and are driven by these gradients. The ultimate role of storms is to decrease the equator-to-pole gradient. The impact of the horizontal temperature gradient is well-known through knowledge of baroclinic instability. A stronger gradient will generally lead to more storminess.

Hernandez-Deckers and von Storch (2012) (hereafter HDvS12) show the second factor, atmospheric stability, is often overlooked in the climate change debate. Stability is simply the atmosphere's resistance to overturning where warm air rises and cold air sinks. For example, to make the atmosphere less (more) stable, one could warm (cool) the surface relative to the upper air.

HDvS12 used the European Centre for Medium Range Forecasting general circulation model (ECHAM5) coupled with an ocean model from the Max Planck Institute. They calculated the generation, flow, and dissipation of energy in the atmosphere in order to compare the impacts of temperature gradient and atmospheric stability in changing the strength of the general circulation.

The authors tested the proposition that AGW will warm the poles faster than the tropics near Earth's surface (SFC, first trial run). This argues for a weakening of the general circulation as horizontal temperature gradients decrease. However, warming the SFC polar region decreased the stability of the model atmosphere. Others have argued AGW will warm the upper troposphere relative to the surface, especially in the tropics (UP, second trial run). This increases tropical atmospheric stability but increases the upper air temperature gradients. HDvS12 then added the two effects together in a third trial (UP+SFC).

HDvS12 found the general circulation "weakens by almost 10% in the UP experiment whereas it strengthens by almost 4% in the SFC experiment. In the FULL experiment, it weakens by about 5%." The FULL and the UP+SFC experiments were similar in outcome. They also note "the expected effects due to mean static [atmospheric] stability and meridional temperature gradient change are opposite of each other." The results demonstrate the stability impact seems to be dominant (Figure 1.4.9.2).

Some scientists have argued storminess should decrease under AGW scenarios due to the weakening

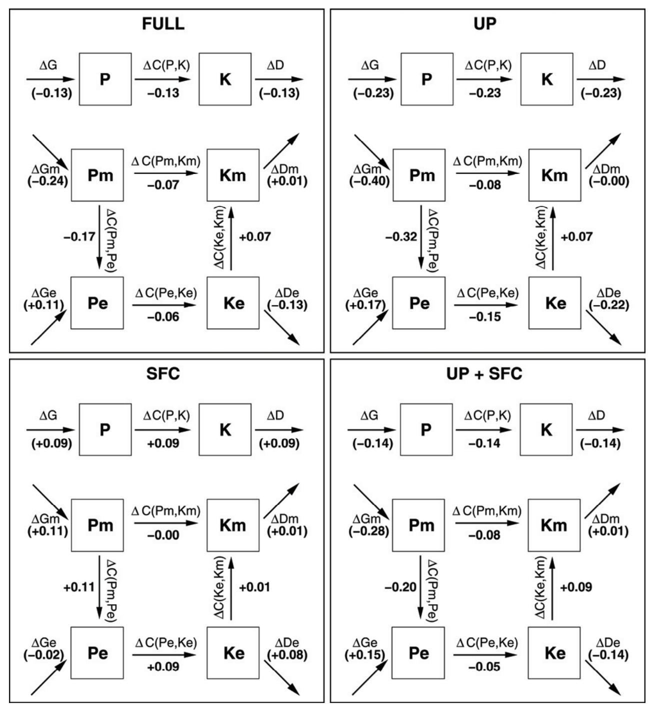

Figure 1.4.9.2. Diagrams of atmospheric energy production, reservoirs, conversions, and dissipation. The numbers given are differences from the control run of the model (today's climate). The FULL, UP, SFC, and UP+SFC, represent an experiment with double CO_2, warmer upper troposphere only, warmer polar surface temperatures only, and the combined effects, respectively. Units are W m^{-2}. Arrows indicate the direction of energy flow. Each square contains a simple two box and a more complex four box energy model. Reprinted with permission from Hernandez-Deckers, D. and von Storch, J.S. 2012. Impact of the warming pattern on global energetics. *Journal of Climate* **25**: 5223–5240.

of the equator-to-pole temperature differences. That is generally correct but overlooks the impact of atmospheric stability. Models have not sorted out the storminess issue because different models employ different physics for processes that affect the temperature gradient. Models also handle the heating effect of CO_2 differently.

These differences have resulted in surface temperature gradients and upper tropospheric warming of various strengths. But as noted in Section 1.4.6.2, there is no strong observational evidence that the upper troposphere is warming as AGW scenarios suggest. HDvS12 demonstrate the utility of models in breaking down complicated climate problems. More importantly, however, model construction clearly can make a significant difference as to how the outcome is interpreted.

Lang and Waugh (2011) note "understanding the characteristics and trends in summer cyclones is important not only for understanding mid-latitude weather systems and extreme events, but it is also important for understanding the Arctic hydrological cycle and radiation budget (e.g., Orsolini and Sortberg, 2009)." In addition, they note "the surface concentrations of ozone and aerosols, and as a result surface air quality, depend on a range of meteorological factors [that] are closely connected with cyclones (e.g., Jacobs and Winner, 2009)."

Lang and Waugh examined "the robustness of trends in Northern Hemisphere (NH) summer cyclones in the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set that was used in the Fourth Assessment (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007)." The two Johns Hopkins University researchers report they could find "little consistency" among the 16 models they studied. They write, "there is no consistency among the models as to whether the frequency of hemispheric-averaged summer cyclones will increase or decrease." For some sub-regions, the sign of the trend was consistent among most of the models, but even then, as they report, "there is still a large spread in the magnitude of the trend from individual models, and, hence, a large uncertainty in the trends from a single model." They conclude, "the general lack of consistency among models indicates that care is required when interpreting projected changes in summer weather systems."

In another study, Zhang *et al.* (2012) examined the behavior of a jet stream in a channel model of similar length to Earth's diameter and about 10,000 km in the "north-south" (meridional) direction, with 17 vertical levels centered on a jet maximum. The simplified model used equations representing the basic conservation laws (mass, momentum, and energy) and allowed the "rotation speed" to vary linearly (in reality, it gets stronger from equator to pole). This model also allowed the variation of atmospheric stability in the meridional direction as well as a meridional temperature difference of 43° C, comparable to terrestrial equator-to-pole temperature differences. The model contained surface friction, varied in order to examine the behavior of the jet.

When the surface friction was increased, the researchers found discernible differences in the zonally and time-averaged wind (Figure 1.4.9.3) and temperature gradient (Figure 1.4.9.4) profiles. The differences were more discernible in the temperature fields, and as the friction was increased, the prominent wave number in the model increased from four to six. Values smaller (greater) than wave numbers four (six) are associated with the larger (smaller) scale that is considered the planetary (synoptic) scale. Annular mode behavior could be found only in the larger-scale "climate" for the model at weak frictional values.

Zhang *et al.* thus demonstrated the importance of larger waves in maintaining large-scale jet stream baroclinicity (density differences) and a baroclinic mechanism for the cooperation between synoptic and large-scale eddies in maintaining the persistence of annular mode behavior. The authors note, "as an internal mode of variability, understanding the mechanism that sustains the zonal wind anomalies is useful not only to predict the intra-seasonal variability in the extra-tropics but also for climate change projections."

These internal variations in the jet stream can represent the maintenance of atmospheric blocking, and both are important to account for in seasonal range forecasting. Also, as the climate changes there may be a change in jet stream behavior, but the internal variations will remain. Conversely, if more complicated models cannot replicate annular mode behavior noted in the observations and the simpler model here in future climate change scenarios, the model projections will be of limited value.

Also exploring the subject were Chang *et al.* (2013), who write that "midlatitude storm tracks are marked by regions frequented by baroclinic waves and their associated surface cyclones," which bring with them "strong winds and heavy precipitation, seriously affecting regional weather and climate."

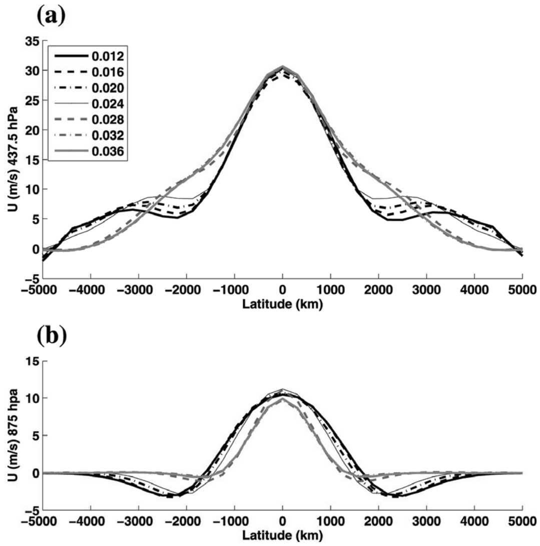

Figure 1.4.9.3. The latitudinal distribution of the zonal and time-averaged zonal winds at (a) 437.5 and (b) 875 hPa for a range of surface friction values. The latitude distance on the abscissa is in kilometers (0 km the channel center). Positive (negative) values are the distance poleward (equatorward). Reprinted with permission from Zhang, Y., Yang, X.Q., Nie, Y., and Chen, G. 2012. Annular mode-like variation in a multilayer quasigeostrophic model. *Journal of the Atmospheric Sciences* **69**: 2940–2958, Figure 3.

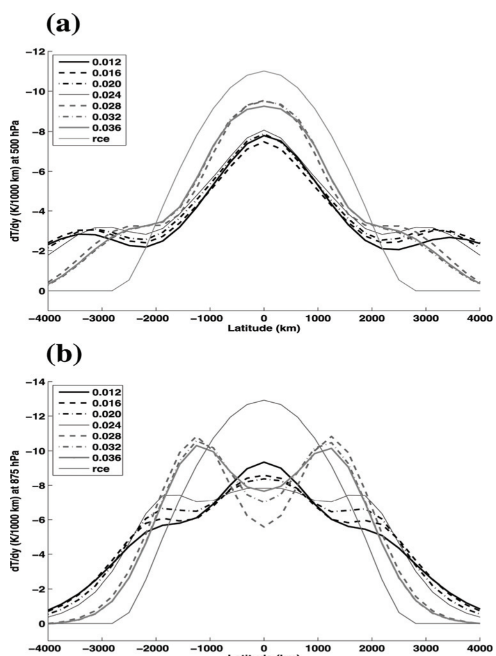

Figure 1.4.9.4. As in Figure 1.4.9.3, except for temperature gradients. Reprinted with permission from Zhang *et al.* (2012), Figure 4.

They also note such storms "transport large amounts of heat, momentum and moisture poleward," making up "an important part of the global circulation," and how these storm tracks may change as a result of global warming "is thus of huge societal interest."

Chang *et al*. used "storm-track activity derived from ERA-Interim [European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala *et al*. 2005)] data as the current best estimate to assess how well models that participated in phase 3 of the Coupled Model Intercomparison Project (CMIP3; Meehl *et al*. 2007) that were considered in the Intergovernmental Panel on Climate Change *Fourth Assessment Report* (Solomon *et al*. 2007) do in simulating storm-track activity."

The four researchers report "only 2 of the 17 models have both the Northern Hemisphere [NH] and Southern Hemisphere [SH] storm-track activity within 10% of that based on ERA-Interim" and "four models simulate storm tracks that are either both significantly (>20%) too strong or too weak." They also note "the SH to NH ratio of storm-track activity ... is biased in some model simulations due to biases in midtropospheric temperature gradients" and "storm tracks in most CMIP3 models exhibit an equatorward bias in both hemispheres." Further, "some models exhibit biases in the amplitude of the seasonal cycle"; "models having a strong (weak) bias in storm-track activity also have a strong (weak) bias in poleward eddy momentum and heat fluxes, suggesting that wave-mean flow interactions may not be accurately simulated by these models"; and "preliminary analyses of *Fifth Assessment Report* (AR5)/CMIP5 model data suggest that CMIP5 model simulations also exhibit somewhat similar behaviors."

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1.4.10 Miscellaneous

Fu *et al*. (2011) note the *Fourth Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concluded climate projections based on models that consider both human and natural factors provide "credible quantitative estimates of future climate change." However, they continue, mismatches between IPCC AR4 model ensembles and observations, especially the multidecadal variability (MDV), "have cast shadows on the confidence of the model-based decadal projections of future climate," as also has been noted by Meehl *et al*. (2009), who indicate considerably more work needs to be done in this important area.

In an exercise designed to illustrate the extent of this model failure, Fu *et al*. evaluated "many individual runs of AR4 models in the simulation of past global mean temperature," focusing on the performance of individual runs of models included in the Coupled Model Intercomparison Project phase 3 (CMIP3) in simulating the multidecadal variability of the past global mean temperature.

The three researchers determined "most of the individual model runs fail to reproduce the MDV of past climate, which may have led to the overestimation of the projection of global warming for the next 40 years or so." More specifically, they note simply taking into account the impact of the Atlantic Multi-decadal Oscillation shows "the global average temperature could level off during the 2020s–2040s," such that the true temperature change between 2011 and 2050 "could be much smaller than the AR4 projection."

Jeong *et al*. (2011) state "the Siberian High (SH) is the most conspicuous pressure system found in the Northern Hemisphere during wintertime," when "strong radiative cooling over the snow covered Eurasian continent forms a cold-core high-pressure system in the lower troposphere over northern Mongolia" that exerts "tremendous influences on weather and climate in Northern Eurasia, East Asia, and even further into South Asia (e.g., Cohen *et al*., 2001; Panagiotopoulos *et al*., 2005; Wang, 2006)." The authors further state SH intensity variations—as simulated by 22 global climate models under 20C3M and A1B scenarios in the CMIP3—show "a steady decreasing trend in the SH intensity from the late 20th century throughout the 21st century, leading to a decrease of about 22% in SH intensity at the end of the 21st century compared to the 1958-1980 average."

In a study designed to determine to what degree the temporal SH intensity simulations of these models mimic reality, Jeong *et al*. employed two observational gridded sea level pressure (SLP) data sets, that of the Hadley Centre and the National Centre for Atmospheric Research, plus two reanalysis data sets (NCEP and ERA40) and *in situ* SLP observations from 20 stations located in the central SH region to create a history of SH intensity over the past several decades.

The climatic reconstructive work of the seven scientists revealed "a pronounced declining trend of the SH intensity from the late 1960s to the early 1990s," which would appear to mesh well with GCM simulations presented in the IPCC AR4 that indicate a "steady weakening of the SH intensity for the entire 21st century." The authors report, however, that in the real world the declining SH intensity trend "was sharply replaced by a fast recovery over the last two decades." The thus note "this feature has not been successfully captured by the GCM simulations used for the IPCC AR4," all of which predict "a steady decreasing trend in the SH intensity from the late 20th century throughout the 21st century."

Jeong *et al*. conclude, "an improvement in predicting the future climate change in regional scale is desirable."

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2

Forcings and Feedbacks

Craig Idso (USA)

Tim Ball (Canada)

Contributing: *Tom Segalstad (Norway)*

Key Findings

Introduction

2.1 Carbon Dioxide
- 2.1.1 Correlation with Temperature
- 2.1.2 Atmospheric Residence Time of CO_2

2.2 Methane
- 2.2.1 Atmospheric Concentrations
- 2.2.2 Emissions to the Atmosphere
- 2.2.3 Extraction from the Atmosphere

2.3 Nitrous Oxide

2.4 Clouds
- 2.4.1 Albedo
- 2.4.2 Cloud Cover

2.5 Aerosols
- 2.5.1 Total Aerosol Effect
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- 2.5.3 Non-Biological

2.6 Other Forcings and Feedbacks
- 2.6.1 Carbon Sequestration
- 2.6.2 Carbonyl Sulfide
- 2.6.3 Diffuse Light
- 2.6.4 Iodocompounds
- 2.6.5 Stratospheric Pertulations
- 2.6.6 Volcanism

Key Findings

The following points summarize the main findings of this chapter:

- Research published in peer-reviewed science journals indicates the model-derived temperature sensitivity of Earth accepted by the IPCC is too large. Negative feedbacks in the climate system reduce that sensitivity to values an order of magnitude smaller.

- Establishing the historic phase relationship between atmospheric carbon dioxide and temperature is a necessary step toward understanding the physical relationship between CO_2 forcing and climate change. When such analyses are conducted, changes in CO_2 are frequently seen to *lag* changes in temperature by several hundred years.

- Many studies reveal a large *uncoupling* of temperature and CO_2 throughout portions of the historical record. Such findings contradict the IPCC's theory that changes in atmospheric CO_2

drive changes in temperature.

- Atmospheric methane observations over the past two decades reside far below the values projected by the IPCC in each of the four *Assessment Reports* it has released to date. The IPCC's temperature projections, which incorporate this inflated influence, should be revised downward to account for this discrepancy.

- Because agriculture accounts for almost half of nitrous oxide (N_2O) emissions in some countries, there is concern that enhanced plant growth due to CO_2 enrichment might increase the amount and warming effect of this greenhouse gas. But field research shows N_2O emissions will likely fall as CO_2 concentrations and temperatures rise, indicating this is actually another negative climate feedback.

- The IPCC has concluded "the net radiative feedback due to all cloud types is likely positive" (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, several studies indicate the net global effect of cloud feedbacks is a cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.

- The IPCC likely underestimates the total cooling effect of aerosols. Studies have found their radiative effect is comparable to or larger than the temperature forcing caused by all the increase in greenhouse gas concentrations recorded since preindustrial times.

- Higher temperatures are known to increase emissions of dimethyl sulfide (DMS) from the world's oceans, which increases the albedo of marine stratus clouds, which has a cooling effect. The IPCC characterizes this chain of events as "a rather weak aerosol-climate feedback at the global scale" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012), but many studies suggest otherwise.

- Several other important negative forcings and feedbacks exist in nature, about which little is known or acknowledged by the IPCC. Such forcings and feedbacks have been shown by multiple scientific studies to significantly influence Earth's climate to a degree comparable to that of projected anthropogenic-induced global warming.

- The IPCC claims a positive feedback exists between climate and the carbon cycle on century to millennial time scales such that a warming climate will result in a loss of carbon storage. There is no empirical evidence to support such an assertion. Just the opposite appears to be the case, as global carbon uptake doubled over the past half-century.

Introduction

Scientists increasingly recognize climate is influenced not only by rising atmospheric carbon dioxide levels, but also other forcings and feedbacks. Even James Hansen—who in 1988 testified before a U.S. Senate Committee that "the global warming is now large enough that we can ascribe with a high degree of confidence a cause-and-effect relationship to the greenhouse effect"—was far more circumspect ten years later as lead author of a paper published in the *Proceedings of the National Academy of Sciences, U.S.A.* (Hansen *et al*., 1998).

Hansen *et al*. examined the forcings of well-mixed greenhouse gases (CO_2, CH_4, N_2O, and CFCs), tropospheric ozone, stratospheric ozone, tropospheric aerosols, forced cloud changes, vegetation and other planetary surface alterations, solar variability, and volcanic aerosols. That examination revealed so many uncertainties in the forcings that the researchers concluded, "the forcings that drive long-term climate change are not known with an accuracy sufficient to define future climate change." Nevertheless, the IPCC has expressed confidence in projections of future climate, saying the temperature sensitivity of Earth's climate system in response to a doubling of atmospheric CO_2 concentrations "is *likely* to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C [italics in the original]" (IPCC, 2007).

The preceding chapter discussed a host of biases and discrepancies that lessen confidence in the ability of models to project future climate. In Chapter 2, we now review important forcings and feedbacks in the climate system. Failure of the models to account properly for the influence of these forcings and feedbacks further erodes confidence in the model projections of climate. Some of the forcings and feedbacks discussed in this chapter may have the potential to offset completely the radiative forcing expected from rising atmospheric CO_2.

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2.1 Carbon Dioxide

When Earth was in its infancy, some 4.5 billion years ago, the atmosphere was predominantly composed of carbon dioxide. At that time, its CO_2 concentration, in terms of the units most commonly used today, would have been at something on the order of 1,000,000 ppm. Ever since, however, the CO_2 content of the air, in the mean, has been dropping.

By 500 million years ago, it is estimated the atmosphere's CO_2 concentration fell to a value of only ~20 times more than it is today, around 7,500 ppm. By 300 million years ago it had declined to close to the air's current CO_2 concentration of 400 ppm, after which it rose to four times that amount at 220 million years before present (Berner 1990, 1992, 1993, 1997; Kasting 1993). During the middle Eocene, some 43 million years ago, the atmospheric CO_2 concentration is estimated to have dropped to a mean value of approximately 385 ppm (Pearson and Palmer, 1999), and between 25 million and 9 million years ago, it is believed to have varied between 180 and 290 ppm (Pagani *et al*., 1999). This last range is essentially the same range over which the air's CO_2 concentration oscillated during the 100,000-year glacial cycles of the past 420,000 years (Fischer *et al*., 1999; Petit *et al*., 1999). With the inception of the Industrial Revolution, the air's CO_2 content has surged upward, now above 400 ppm with the promise of significantly higher concentrations to come.

In addition to its variation over geologic time, the atmosphere's CO_2 concentration exhibits a seasonal variation. It declines when terrestrial vegetation awakens from the dormancy of winter and begins to grow in the spring, thereby extracting great quantities of CO_2 from the air; and it rises in the fall and winter, when much of the biomass produced over the summer dies and decomposes, releasing great quantities of CO_2 back to the atmosphere.

The air's CO_2 content also varies spatially over the surface of Earth. Most spectacular in this regard are the local concentration enhancements observed over large metropolitan areas due to high levels of vehicular traffic and commercial activities. Idso *et al*. (1998a, b), for example, measured CO_2 concentrations near the center of Phoenix, Arizona that were 50 percent greater than those measured over surrounding rural areas. Significant enhancements of the air's CO_2 concentration also may be observed in the vicinity of burning coal seams and naturally occurring high-CO_2 springs.

Given the radiative properties of atmospheric CO_2, concerns have been expressed for some time that rising levels of CO_2 may lead to a significant warming of the planet. The IPCC supports such a hypothesis of future CO_2-induced climate change, and it also has concluded the modern rise of atmospheric CO_2 is affecting the climate *now*. Writing in its *Fifth Assessment Report* (FAR), the IPCC states

> Globally, CO_2 is the strongest driver of climate change compared to other changes in the atmospheric composition, and changes in surface conditions [since the Industrial Revolution]. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers. CO_2 concentrations and rates of increase are unprecedented in the last 800,000 years and at least 20,000 years, respectively (Summary for Policy Makers, Second Order Draft of AR5, October 5, 2012, p. 7).

Research suggests, however, that the IPCC's view of atmospheric CO_2 as "the strongest driver of climate change" should be reconsidered if not outright rejected. The studies reviewed here find it is likely rising atmospheric CO_2 concentrations will have little impact on future climate.

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2.1.1 Correlation with Temperature

According to the IPCC, the global warming of the mid- to late twentieth century and early twenty-first century was caused primarily by the rise in atmospheric CO_2 concentration. This assertion is controversial (see Smagorinsky *et al*. (1982) and Idso (1982) for early pro/con positions on the issue), and with the retrieval and preliminary analysis of the first long ice core from Vostok, Antarctica—which provided a 150,000-year history of both surface air temperature and atmospheric CO_2 concentration—the debate became even more intense. The close associations of the ups and downs of atmospheric CO_2 and temperature evident during glacial terminations and inceptions in that record, as well as in subsequent records of even greater length, led many supporters of the CO_2-induced global warming theory to assert those observations proved anthropogenic CO_2 emissions were responsible for twentieth century global warming.

This contention was challenged by Idso (1989), who wrote, "changes in atmospheric CO_2 content never precede changes in air temperature, when going from glacial to interglacial conditions; and when going from interglacial to glacial conditions, the change in CO_2 concentration actually lags the change in air temperature (Genthon *et al*., 1987)." He thus concludes, "changes in CO_2 concentration cannot be claimed to be the cause of changes in air temperature, for the appropriate sequence of events (temperature change following CO_2 change) is not only never present, it is actually violated in [at least] half of the record (Idso, 1988)."

The following subsections expand on such research. Our understanding of the relationship between atmospheric CO_2 and temperature has improved in the years since, clearly demonstrating the lack of a causal link.

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2.1.1.1 Geologic Epochs

Rothman (2002) derived a 500-million-year history of the air's CO_2 content based on considerations related to the chemical weathering of rocks, volcanic and metamorphic degassing, and the burial of organic carbon, along with considerations of the isotopic content of organic carbon and strontium in marine sedimentary rocks. This analysis suggests over the majority of the half-billion-year record, Earth's atmospheric CO_2 concentration fluctuated between values two to four times greater than those of today at a dominant period on the order of 100 million years (see Figure 2.1.1.1.1). Over the past 175 million years, however, the data depict a long-term decline in the air's CO_2 content.

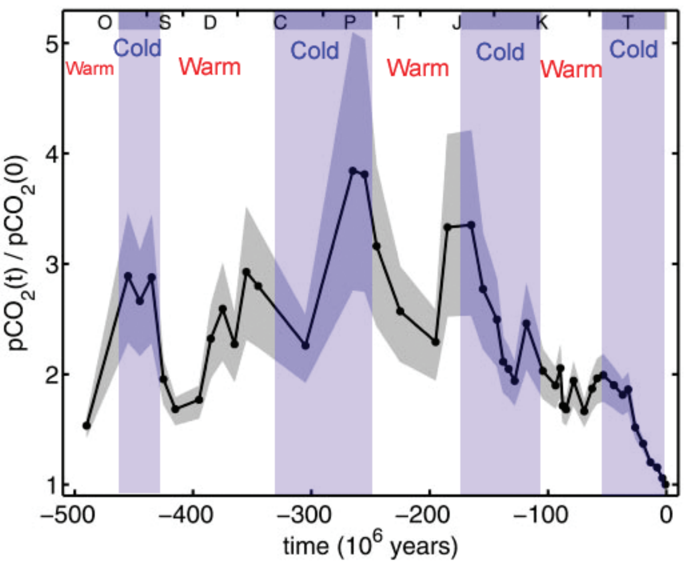

Figure 2.1.1.1.1. A 500-million-year record of the atmosphere's CO_2 concentration (relative to that of the present = 1) together with indications of periods of relative cold and warmth. Adapted from Rothman, D.H. 2002. Atmospheric carbon dioxide levels for the last 500 million years. *Proceedings of the National Academy of Sciences USA* **99**: 4167–4171.

With respect to the question of what correspondence might exist between ancient climates and atmospheric CO_2 concentrations, Rothman states the CO_2 history of Figure 2.1.1.1.1 "exhibits no systematic correspondence with the geologic record of climatic variations at tectonic time scales." A visual examination of Rothman's plot of CO_2 and concomitant major cold and warm periods clearly indicates the three most striking peaks in the air's CO_2 concentration occur either totally or partially within periods of time when Earth's climate was relatively cool. Not only is there no support in these data for the claim that high atmospheric CO_2 concentrations tend to warm the planet, the data suggest there are times in Earth's history when just the opposite was the case.

Focusing on the middle Eocene climate of 43 million years ago, Pearson and Palmer (1999) report the planet then may have been as much as 5°C warmer than today, yet the mean CO_2 concentration of the atmosphere, as determined by pH data inferred from boron isotope composition in planktonic foraminifera, was only about 385 ppm.

Much the same was found by these authors one year later in an analysis of atmospheric CO_2 and temperature over the past 60 million years (Pearson and Palmer, 2000). Sixty million years before present (BP), the authors note, the atmosphere's CO_2 concentration, shown at the left in Figure 2.1.1.1.2, was approximately 3,600 ppm and the oxygen isotope ratio (at the right in the figure) was about 0.3 per mil (Figure 2.1.1.1.2, orange highlight). Thirteen million years later, the air's CO_2 concentration had dropped to 500 ppm, yet the oxygen isotope ratio dropped (implying a rise in temperature) to zero. That is just the opposite of what one would expect were CO_2 the driver of climate change.

Next comes a large spike in the air's CO_2 content, all the way up to a value of 2,400 ppm (Figure 2.1.1.1.2, blue). What does the oxygen isotope ratio do at that time? It rises slightly (implying the temperature falls slightly) to about 0.4 per mil, again just the opposite of what one would expect under the CO_2-induced global warming hypothesis.

After the spike in CO_2, the air's CO_2 concentration drops dramatically, declining to a minimum value of close to what it is today (Figure 2.1.1.1.2, purple). The oxygen isotope ratio barely changes at all, defying once again the assumption of the CO_2-induced global warming hypothesis.

Between this point and the break in the record at 40 million years BP, the air's CO_2 concentration rises again to approximately 1,000 ppm, and the oxygen isotope ratio rises slightly (implying a slight cooling) to 0.6 per mil (Figure 2.1.1.1.2, blue). Again, the common assumption of the CO_2-induced global warming hypothesis—that changes in atmospheric CO_2 drive changes in air temperature—fails.

Picking up the record at 24 million years BP, there are relatively tiny variations in atmospheric CO_2 concentration up to the present but large variations in oxygen isotope values, both up and down, again in clear contradiction of the CO_2-induced global warming hypothesis (Figure 2.1.1.1.2, yellow). The most interesting of these oxygen isotope changes is the dramatic increase (implying a dramatic cooling) over the most recent two million years, when the air's

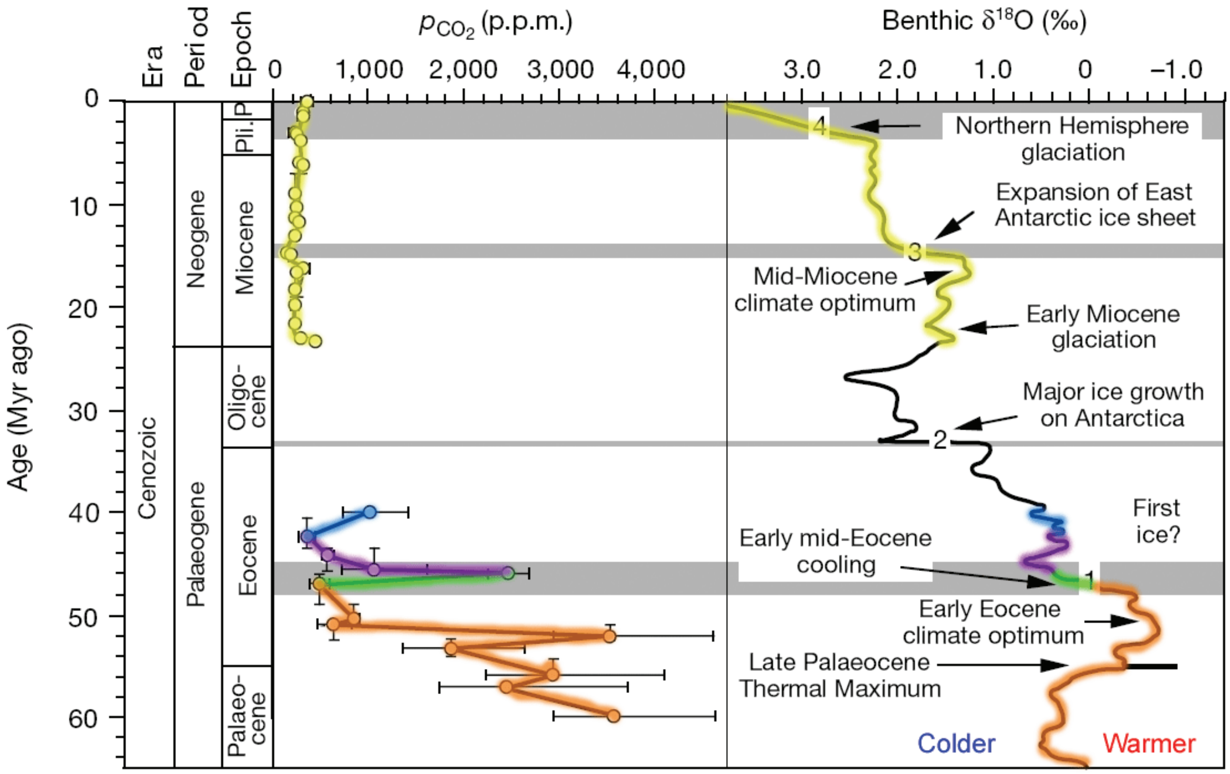

Figure 2.1.1.1.2. Atmospheric CO_2 concentration and proxy temperature over the past 60 million years. Adapted from Pearson, P.N. and Palmer, M.R. 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature* **406**: 695–699.

CO_2 concentration has risen slightly.

In another detailed review of Earth's thermal and CO_2 history, Pagani *et al*. (2005) examined these parameters over the most recent 50 million years. Their examination revealed essentially the same findings as the study of Pearson and Palmer (2000). As demonstrated in Figure 2.1.1.1.3, about 43 million years ago the atmosphere's CO_2 concentration was approximately 1,400 ppm and the oxygen isotope ratio (a proxy for temperature) was about 1.0 per mil. Then, over the next ten million years, the air's CO_2 concentration underwent three huge oscillations on the order of 1,000 ppm from peak to valley (Figure 2.1.1.1.3, red). In the first two oscillations, temperature appeared not to respond at all, exhibiting an uninterrupted slow decline represented by the steady upward trend in $\delta^{18}O$. Following the third rise in CO_2, however, temperatures seemed to respond, but in the opposite direction to what is expected according to the CO_2-induced global warming hypothesis—the rise in CO_2 was followed by the sharpest drop in temperature (rise in $\delta^{18}O$) of the entire record.

Following this large drop in temperature between 34 and 33 million years before present (Ma BP), the oxygen isotope ratio hovered around a value of 2.7 per mil from about 33 to 26 Ma BP, indicating little change in temperature over that period. The corresponding CO_2 concentration (Figure 2.1.1.1.3, green) was anything but constant, experiencing about a 500 ppm increase around 32 Ma BP, after which it dropped a full 1,000 ppm over the next two million years, only to rise again by a few hundred ppm, repeatedly defying the common causal assumption of the CO_2-induced global warming hypothesis.

Around 26 Ma BP, the oxygen isotope ratio dropped to about 1.4 per mil (implying a significant rise in temperature), during which time the air's CO_2 content (Figure 2.1.1.1.3, yellow) declined, once again the opposite of what one would expect were CO_2 driving climate change. Then, from 24 Ma BP to the end of the record at 5 Ma BP, there were relatively tiny variations in the atmosphere's CO_2 content (Figure 2.1.1.1.3, blue) but large variations in oxygen isotope values, both up and down.

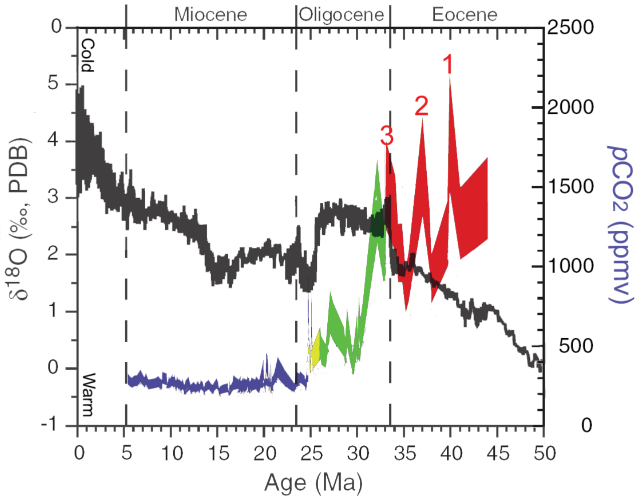

Figure 2.1.1.1.3. Atmospheric CO_2 concentration (multicolored line) and proxy temperature (black line) over the past 50 million years. Adapted from Pagani, M., Zachos, J.C., Freeman, K.H., Tipple, B., and Bohaty, S. 2005. Marked decline in atmospheric carbon dioxide concentrations during the Paleogene. *Science* **309**: 600–603.

These observations, according to Pagani *et al.* (2005), "argue for a decoupling between global climate and CO_2" and stand in clear contradiction of the CO_2-induced global warming hypothesis.

Pagani *et al.* (1999), working with sediment cores from three deep-sea drilling sites, also found the air's CO_2 concentration to be uniformly low (180 to 290 ppm) throughout the early to late Miocene (25 to 9 million years ago), at a time when deep-water and high-latitude surface water temperatures were as much as 6°C warmer than today. They stated their finding "appears in conflict with greenhouse theories of climate change." In addition, they noted the air's CO_2 concentration seemed to rise after the expansion of the East Antarctic Ice Sheet, also in conflict with greenhouse theories of climate change.

Considered in their entirety, the results of these studies present a truly chaotic picture with respect to any possible effect variations in atmospheric CO_2 concentration may have on global temperature. The IPCC has neglected to adequately address the inconsistency between these real-world observations and the model-based projections in their reports.

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2.1.1.2 Pleistocene Glacial/Interglacial Cycles

Several studies have shed additional light on the relationship between CO_2 and temperature as manifested throughout the past 800,000 years of dramatic glacial-interglacial climate cycles.

Fischer *et al.* (1999), for example, examined trends of atmospheric CO_2 and air temperature derived from Antarctic ice core data extending back 250,000 years. Over this period, the three most dramatic warming events experienced on Earth were the terminations of the last three ice ages; for each of these climatic transitions, Earth's air temperature always rose well in advance of the increase in atmospheric CO_2. In each transition, the air's CO_2 content did not begin to rise until 400 to 1,000 years after the planet began to warm.

Another team to study the CO_2–temperature relationship was that of Petit *et al.* (1999), who discovered during all glacial inceptions of the past half-million years, temperature always dropped well before the decline in the air's CO_2 concentration. They conclude their data indicate "the CO_2 decrease lags the temperature decrease by several thousand years." Likewise, Mudelsee (2001) determined variations in atmospheric CO_2 concentration lagged behind variations in air temperature by 1,300 to 5,000 years over the past 420,000 years. In addition, during certain climatic transitions characterized by rapid warmings of several degrees, which were followed by slower coolings that returned the climate to essentially full glacial conditions, Staufer *et al*. (1998) observe the atmospheric CO_2 concentration derived from ice core records typically varied by less than 10 ppm. They, too, consider the CO_2 perturbations to have been caused by the changes in climate, rather than vice versa.

Many other studies have demonstrated this reverse coupling of atmospheric CO_2 and temperature (Cheddadi *et al*., 1998; Gagan *et al*., 1998; Raymo *et al*., 1998), where temperature is the independent variable that appears to induce changes in CO_2. In addition, Steig (1999) noted cases of the inverse coupling of the two parameters, showing between 7,000 and 5,000 years ago, atmospheric CO_2 concentrations increased by just over 10 ppm at a time when temperatures in both hemispheres cooled.

Caillon *et al*. (2003) measured the isotopic composition of argon—specifically, δ^{40}Ar, which they argued "can be taken as a climate proxy, thus providing constraints about the timing of CO_2 and climate change"—in air bubbles in the Vostok ice core over the period that comprises what is called Glacial Termination III, about 240,000 years ago. The results of their meticulous analysis led them to conclude "the CO_2 increase lagged Antarctic deglacial warming by 800 ± 200 years" (see Figure 2.1.1.2.1)

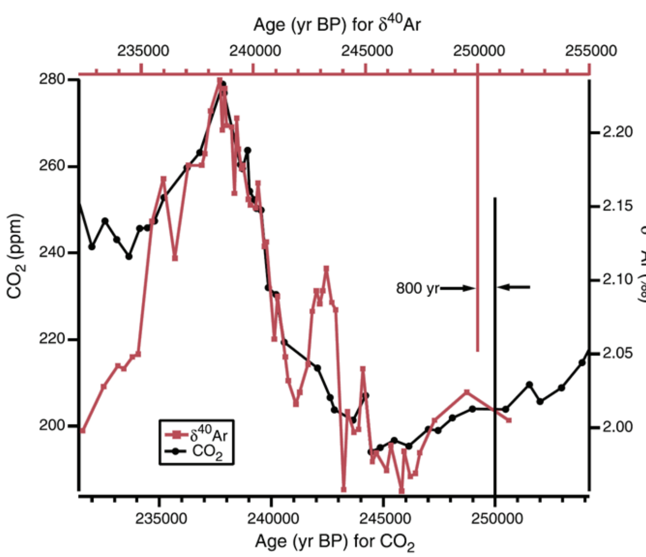

Figure 2.1.1.2.1. Isotopic argon and CO_2 values from Vostok Ice core air bubbles. Note the 800 year offset between the top (δ^{40}Ar) and bottom (CO_2) axes for Age (yr BP). Reprinted with permission from Caillon, N., Severinghaus, J.P., Jouzel, J., Barnola, J.-M., Kang, J., and Lipenkov, V.Y. 2003. Timing of atmospheric CO_2 and Antarctic temperature changes across Termination III. *Science* **299**: 1728–1731.

This finding, in the words of Caillon *et al*., "confirms that CO_2 is not the forcing that initially drives the climatic system during a deglaciation." Nevertheless, they and others continue to hold the view that the subsequent increase in atmospheric CO_2—believed to be due to warming-induced CO_2 outgassing from the world's oceans—serves to amplify the warming caused by whatever prompts the temperature to rise in the first place. This supposition is founded on unproven assumptions about the strength of CO_2-induced warming and is applied without any regard for biologically induced negative climate feedbacks that may occur in response to atmospheric CO_2 enrichment, as discussed later in this chapter. Moreover, there is no way to objectively determine the strength of the proposed amplification from the ice core data.

In light of these observations, the role of CO_2 as a primary driver of climate change on Earth would appear to be disproved; the CO_2 warming amplification hypothesis appears unlikely as well.

Another departure from standard greenhouse effect theory occurred over the 17,000-year period following the penultimate deglaciation, when the air's CO_2 content was essentially constant but air temperature declined to values characteristic of glacial times (see Figure 2.1.1.2.2). An even greater contradiction of IPCC-based thinking occurred immediately thereafter, when CO_2 finally began to fall but temperature began to rise.

Also discovering an inverse greenhouse gas/temperature relationship were Indermuhle *et al*. (1999), who determined after the termination of the last great ice age the CO_2 content of the air gradually rose by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, over a period of slow but steady decline in global air temperature. A year later, working with a high-resolution temperature and atmospheric CO_2 record spanning the period 60 to 20 thousand years ago, Indermuhle *et al*. (2000) discovered four distinct periods when temperatures rose by approximately 2°C and CO_2 rose by about 20 ppm. One of the statistical tests they performed on the data suggests the shifts in the air's CO_2 content during these intervals *followed* the shifts in air temperature by approximately 900 years, and a second statistical test yielded a mean CO_2 lag time of 1,200 years.

Another pertinent study comes from Siegenthaler *et al*. (2005), who analyzed CO_2 and temperature proxy (δD, the ratio of deuterium to hydrogen) data derived from an ice core in Antarctica. Results of

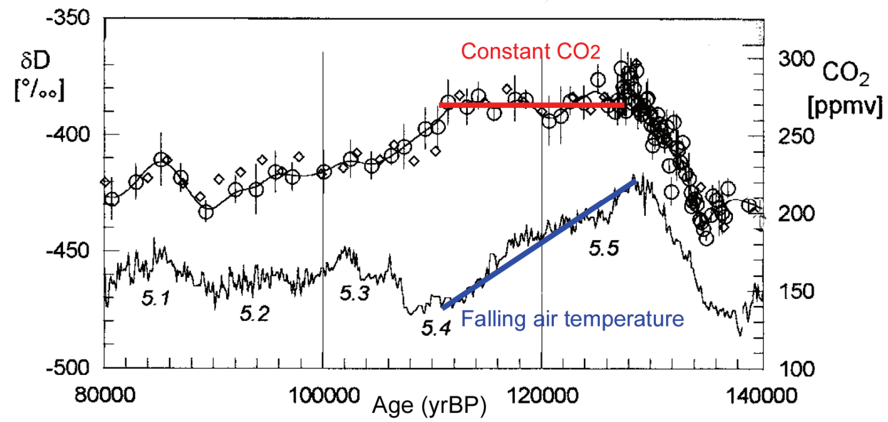

Figure 2.1.1.2.2. Atmospheric CO_2 and proxy temperature. Adapted from Fischer, H., Wahlen, M., Smith, J., Mastroianni, D., and Deck, B. 1999. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**: 1712–1714..

their analysis revealed a coupling of Antarctic temperature and CO_2 in which they obtained the best correlation between CO_2 and temperature "for a lag of CO_2 of 1900 years." Over the course of glacial terminations V to VII, they observe "the highest correlation of CO_2 and deuterium, with use of a 20-ky window for each termination, yields a lag of CO_2 to deuterium of 800, 1600, and 2800 years, respectively." In addition, they note "this value is consistent with estimates based on data from the past four glacial cycles," citing the work of Fischer *et al.* (1999), Monnin *et al.* (2001), and Caillon *et al.* (2003). This too confirms temperature leads this tightly coupled relationship, while CO_2 lags, possibly providing only a fraction (which could well be miniscule) of the total glacial-to-interglacial temperature change.

Such observations do little to inspire confidence in projections that the CO_2 produced by the burning of fossil fuels will lead to significant global warming, where predicted warmings in some scenarios rival those experienced in glacial-to-interglacial transitions. Nevertheless, Siegenthaler *et al.* maintained the new findings "do not cast doubt ... on the importance of CO_2 as a key amplification factor of the large observed temperature variations of glacial cycles." However, it should be noted that when temperature leads CO_2 by thousands of years, during both glacial terminations and inceptions (Genthon *et al.*, 1987; Fischer *et al.*, 1999; Petit *et al.*, 1999; Indermuhle *et al.*, 2000; Monnin *et al.*, 2001; Mudelsee, 2001; Caillon *et al.*, 2003), there is ample reason to conclude CO_2 plays but a minor role in enhancing temperature changes that are clearly induced by something else.

Thomas Stocker (the second and corresponding author of the Siegenthaler *et al.* paper) was quoted by the BBC's Richard Black (BBC News, 24 Nov 2005) as saying the relationship they observed between δD and CO_2 is "a very strong indication of the important role of CO_2 in climate regulation." A more plausible statement, however, would be that the relationship is "a very strong indication of the important role of climate in CO_2 regulation." As evidenced by 650,000 years of real-world data, wherever temperature went over this period, CO_2 (mostly) followed.

Still other papers have chipped away at the IPCC-led hypothesis that atmospheric CO_2 is and will be the dominant driver of climate change both now and in the future.

Kirchner (2002) present a pair of interesting graphs, the first of which is a plot of temperature vs. atmospheric CO_2 concentration he derived from 400,000 years of Vostok ice core data, adapted as Figure 2.1.1.2.3. The plot in this graphic displays a fair amount of scatter but seems to suggest the existence of a crude linear relationship between the two variables, which is what Kirchner implied by drawing a best-fit linear regression line through the data (the solid dark red line).

However, the data may be equally well characterized as a two-dimensional distribution, such as that shown in Figure 2.1.1.2.4. The apex is anchored at the point defined by the coldest temperature and lowest CO_2 concentration of the data set. Rather than a crude linear relationship between temperature and CO_2, this "slice of pie" characterization may be preferred, for when the current temperature–CO_2 state of the world is plotted, it falls far below the linear relationship derived by Kirchner but right on the lower side of the piece of pie we would place over the data.

With respect to the meaning of the plotted relationship, Kirchner notes "despite greenhouse gas concentrations that are unprecedented in recent Earth

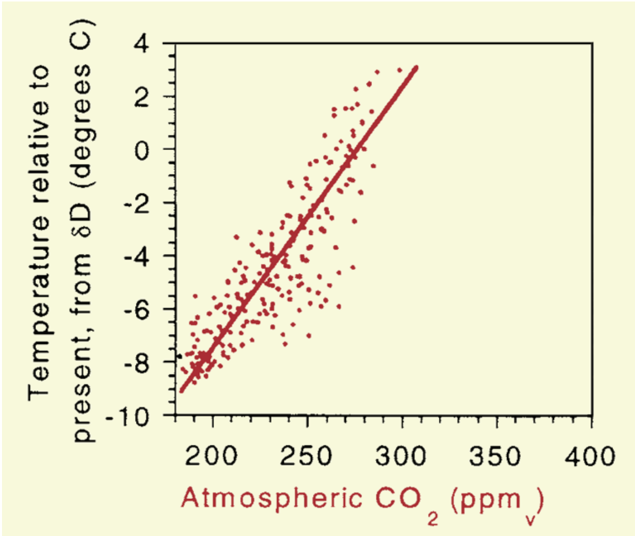

Figure 2.1.1.2.3. Scatter-plot of Vostok ice core-derived atmospheric CO_2 and proxy temperature data over the last 400,000 years. Adapted from Kirchner, J.W. 2002. The Gaia Hypothesis: fact, theory, and wishful thinking. *Climatic Change* **52**: 391–408..

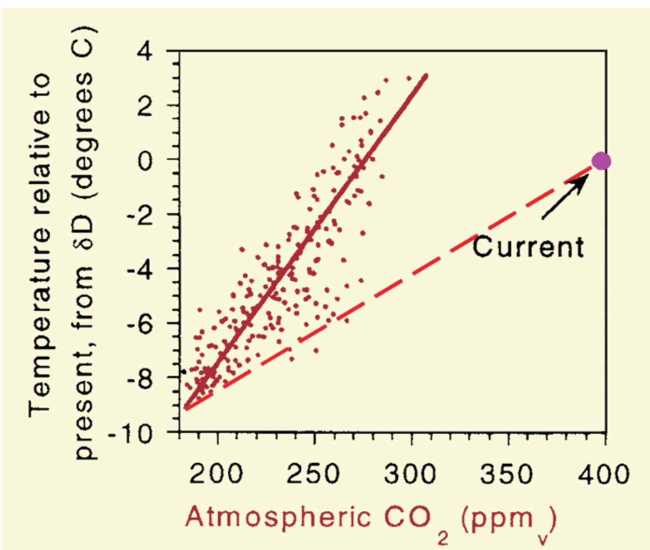

Figure 2.1.1.2.4. Adapted from Kirchner 2002, same as Figure 2.1.1.2.3, but with the current CO_2 concentration of the atmosphere and the dashed red line added.

history, global temperatures have not (yet) risen nearly as much as the correlations in the ice core records would indicate that they could." He pointed out, for example, that his representation of the ice core data suggests "for the current composition of the atmosphere, current temperatures are anomalously cool by many degrees." Kirchner's work suggests the anomaly is approximately 10°C, significantly more than the maximum warming currently predicted by the Intergovernmental Panel on Climate Change to accompany a doubling of the air's CO_2 content. One might also say the data as depicted in Figure 2.1.1.2.4 suggests Earth's current temperature is not "anomalous" at all.

Kirchner's second graph (not shown), a plot of temperature vs. atmospheric methane concentration, is also of interest. The relationship described by the data is absolutely and unquestionably linear and exhibits very little scatter. When used to compute what the temperature of today's Earth "should be," on the basis of the current atmospheric methane concentration, the result is fully 40°C more than the planet's current temperature. This graphic too provides no basis for characterizing Earth's current temperature as anomalous. Instead, in both the case of methane and of CO_2, it is the atmospheric greenhouse gas concentration that is anomalous.

Since Kirchner's temperature vs. atmospheric methane concentration plot reveals such a tight coupling of temperature and methane, but the relationship between the two is such that methane cannot be the determinant of temperature, it must be concluded that temperature is the determinant of atmospheric methane concentration … as long as humanity is not a part of the picture.

For nearly all of the past 400,000 years, this restriction has applied. As humanity's population and impact on the biosphere have grown over the past few centuries, however, this relationship has been outgrown, causing the atmosphere's methane concentration to rise to levels far above anything experienced throughout the history of the Vostok ice core. But Earth's temperature has not responded to the anthropogenic-induced methane increase and is currently about 3°C cooler than it was during the peak warmth of the prior 400,000 years (Figure 2.1.1.2.5), when the air's methane concentration was only 40 percent of what it is today.

A similar conclusion can be reached about temperature and atmospheric CO_2 concentration: It is temperature change that elicits changes in the air's CO_2 content and not vice versa, although the scatter in Kirchner's temperature vs. atmospheric CO_2 concentration plot is sufficient to allow for significant independent movement by both of these parameters. The conclusion that atmospheric CO_2 concentration is not a major determinant of Earth's temperature is supported by the fact that Earth is currently about 3°C cooler than it was during the peak warmth of the prior

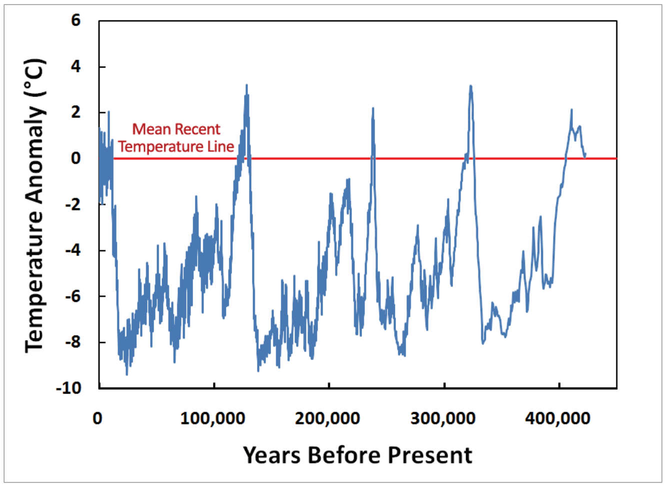

Figure 2.1.1.2.5. Proxy temperatures going back 420,000 years, based on tabular data presented in Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.

four interglacials, when the air's CO_2 content was only about 75 percent of what it is today.

When considering the above observations together, the findings are remarkable. Since the occurrence of the peak temperature of the past 400,000 years, the concentrations of the two most powerful greenhouse gases in the atmosphere (exclusive of water vapor)—CO_2 and methane—have increased by approximately a third and 2.5-fold, respectively, yet Earth's temperature has fallen by 3°C. Clearly, CO_2 and methane are not the important drivers of climate change the IPCC and others consider them to be.

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2.1.1.3 Holocene

Several researchers have examined the relationship between atmospheric CO_2 and temperature during the transition from the glacial conditions of the last ice age to the interglacial conditions of the present Holocene. As in the studies examined in the preceding two sections, their data reveal a number of problems with the IPCC-based hypothesis that rising CO_2 will cause unprecedented warming of the planet.

Focusing on the period between 22,000 and 9,000 years ago, Monnin *et al*. (2001) found the start of the CO_2 increase lagged the start of the temperature increase by 800 years. An analysis of this most recent glacial/interglacial transition by Yokoyama *et al*. (2000), which also has been discussed by Clark and Mix (2000), revealed a rapid rise in sea level, caused by the melting of land-based ice that began approximately 19,000 years ago, preceded the post-glacial rise in atmospheric CO_2 concentration by about 3,000 years. Only after a couple thousand years did CO_2 concentration catch up with the sea level rise.

Stott *et al*. (2007) state establishing "the exact phasing of events during glacial terminations" is "a necessary step in understanding the physical relation between CO_2 forcing and climate change." Working with a marine sediment core from the western tropical Pacific Ocean, Stott *et al*. set out to determine "the chronology of high- and low-latitude climate change at the last glacial termination by radiocarbon dating benthic and planktonic foraminiferal stable isotope and magnesium/calcium records." This provided a temporal resolution of 25 to 50 years for each sample over the period stretching from 10 thousand to 22 thousand years before the present. The research team found "deep-sea temperatures warmed by ~2°C between 19 and 17 thousand years before the present, leading the rise in atmospheric CO_2 and tropical-surface-ocean warming by ~1000 years."

Stott *et al*. conclude the cause of the deglacial deep-water warming "does not lie within the tropics, nor can its early onset between 19 and 17 thousand years before the present be attributed to CO_2 forcing." And since the rate of deep-water warming did not increase after the start of the increase in the atmosphere's CO_2 concentration (if anything, it declined), there is no compelling reason to infer the deglacial increase in the air's CO_2 content had anything to do with the warming that led to the ultimate development of the current interglacial.

Working in Africa, Tierney *et al*. (2008) report the initiation of the deglacial warming in southeast Africa "is consistent with rising temperatures at ~20,000 years B.P. in Antarctica," but they add the deglacial warming "leads the deglacial CO_2 rise recorded in Antarctic ice cores by about 3,000 years." They describe this as "a difference that is outside the chronological errors of the ice core and the lake surface temperature records." Tierney *et al*. conclude "increasing greenhouse gas concentrations are therefore not responsible for the initial transmission of warming from the high latitudes to the southeast African tropics."

McElwain *et al*. (2002) derived high-resolution (approximately 20- to 37-year accuracy) atmospheric CO_2 histories from stomatal frequencies measured on subfossil leaves of *Dryas integrifolia*, *Picea mariana*, *P. glauca,* and *Larix laricina* obtained from sediment cores extracted from two sites in New Brunswick, Canada that contained material spanning the period from approximately 13,000 to 10,500 years ago. Their data reveal an abrupt drop in atmospheric CO_2 concentration of approximately 75 ppm at the onset of the Younger Dryas cold event. This drop in CO_2 lagged the event-defining temperature drop by approximately 130 years. Then, at the end of the Younger Dryas, there was a rapid rise in atmospheric CO_2 concentration that was (within the time-resolution error bounds of the data) essentially coeval with the increase in temperature that brought an end to the Younger Dryas and initiated the Holocene. In absolute terms, the pre-Younger Dryas CO_2 concentration was approximately 300 to 320 ppm, the concentration during the Younger Dryas interval approximately 235 ppm, and the concentration immediately afterwards in the range of 285 to 300 ppm.

Comparing their results with atmospheric CO_2 concentrations derived from polar ice core data, the authors note the best such data available had time resolutions of approximately 200 to 550 years. Degrading (averaging) their data accordingly, they were able to closely match the ice core results, a steady increase in atmospheric CO_2 concentration from the beginning to the end of the Younger Dryas interval. But the ice core data could not mimic the much-finer-scale story told by their data, including the dramatic decline in atmospheric CO_2

concentration at the inception of the Younger Dryas and the dramatic increase in the air's CO_2 content at the conclusion of the cold event.

That the decline in atmospheric CO_2 concentration at the onset of the Younger Dryas lagged the decline in temperature by some 130 years clearly demonstrates the change in the air's CO_2 content did not cause the change in temperature, but that the temperature drop—or whatever caused it—was responsible for the decline in CO_2 concentration. There is little reason to believe the same was not true at the end of the Younger Dryas, although the authors' data resolution was not good enough to explicitly demonstrate that fact.

Other studies have demonstrated a complete uncoupling of CO_2 and temperature (Cheddadi *et al*., 1998; Gagan *et al*., 1998; Raymo *et al*., 1998). Indermuhle *et al*. (1999) demonstrated after the termination of the last great ice age, the CO_2 content of the air gradually rose by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, during a period of time that manifested a slow but steady decline in mean global air temperature. Steig (1999) found between 7,000 and 5,000 years ago, atmospheric CO_2 concentrations increased by just over 10 ppm while temperatures in both hemispheres cooled. These results are just the opposite of what would be expected if changes in atmospheric CO_2 drove climate change as claimed by the CO_2-greenhouse effect theory.

The case for an uncoupling of CO_2 and temperature is driven home further by an examination of the long-term temperature record produced by the Greenland Ice Sheet Project (GISP2), depicted in Figure 2.1.1.3.1 as plotted by Drake (2012) and based on data reported by Alley (2004).

It is most interesting to note that over its first 4,800 years (fully 96 percent of the record), when temperature varied widely, the atmosphere's CO_2 concentration was extremely stable, between about 275 and 285 ppm, whereas over the past 200 years (the remaining 4 percent of the record), when the temperature shows but a fraction of a degree warming, the air's CO_2 concentration rose by more than an extra 100 ppm.

Although almost any long-term temperature history could be used to make this point, it is clear from this simple example that the air's CO_2 content is not a major driver of Earth's temperature. It may not even be a minor driver, and it may have even less of an effect on climate in the not-so-distant future as the population of the world reaches a peak.

Consider, for example, the work of Idso (1989), who derived a predictive relationship based on world population and atmospheric CO_2 concentration data, updated and presented here as Figure 2.1.1.3.2. The

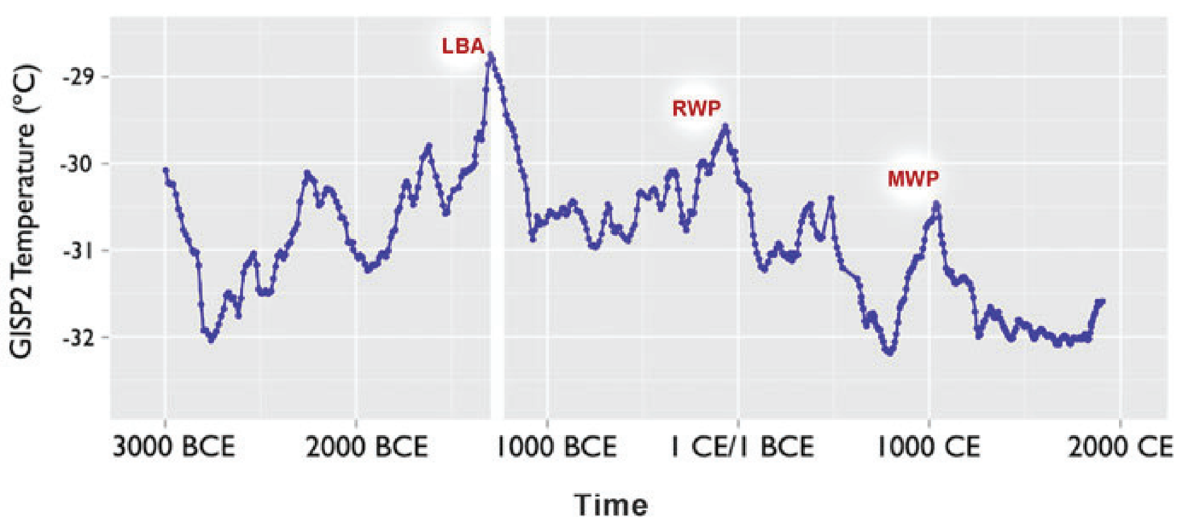

Figure 2.1.1.3.1. The past 5,000 years of the GISP2 temperature history of the Greenland Ice Sheet with general locations of the Late Bronze Age (LBA), the Roman Warm Period (RWP), and the Medieval Warm Period (MWP) indicated. Adapted from Drake, B.L. 2012. The influence of climatic change on the Late Bronze Age Collapse and the Greek Dark Ages. *Journal of Archaeological Science* **39**: 1862–1870.

figure depicts a linear relationship between global population (an alternative representation of CO_2 emissions) and atmospheric CO_2 concentration, a relationship that has endured over time in spite of ongoing and sometimes rapid changes in energy sources and the energy mix as society has industrialized and modernized. That this relationship has remained steady over time is remarkable.

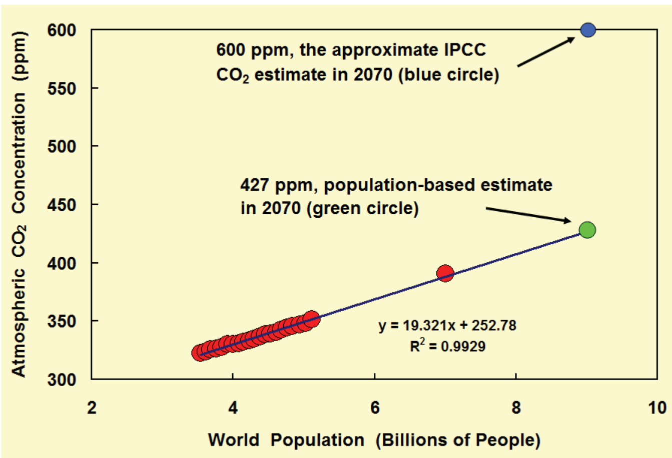

Figure 2.1.1.3.2. Atmospheric CO_2 concentration vs. world population based on data presented by Idso (1989), updated to 2011, the year Earth's population reached the seven billion mark. The linear regression line has been extrapolated to a population of nine billion persons. The IPCC-based projected CO_2 concentration in 2050 is also presented (blue circle). See Idso, S.B. 1989. *Carbon Dioxide and Global Change: Earth in Transition*. Tempe AZ: IBR Press.

The original linear relationship has been extended here to a world population of nine billion people, which is where Lutz *et al*. (2001) calculate the population of the planet will peak in the year 2070, according to the median result of their several projections. At this population, using the linear regression relationship depicted, an atmospheric CO_2 concentration of 427 ppm is calculated. Beyond this point in time, the peak in global population, the relationship suggests atmospheric CO_2 levels may level off and begin to drop as the planet's population stabilizes and/or begins to decline.

Such a conclusion is dramatically at odds with the IPCC projections, which predict far greater CO_2 concentrations for far greater times to come, but is likely far more robust. The equation derived in the above figure, for example, is based on data since 1650. For the past three-and-a-half centuries it has performed marvelously, including over the period of dramatic global population growth, during large changes in both the global source and mix of energy, and over the period of rapid growth in anthropogenic CO_2 emissions that occurred after World War II, suggesting this relationship will not suddenly cease to apply over the next six decades when the planet's population peaks. Although there may be slight variations ahead, they likely will be so small as to be essentially insignificant.

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2.1.2 Atmospheric Residence Time of CO_2

In a paper published in the international peer-reviewed journal *Energy & Fuels*, Dr. Robert H. Essenhigh, professor of energy conversion at The Ohio State University, addressed the residence time (RT) of anthropogenic CO_2 in the air. Essenhigh (2009) notes the IPCC in its first report (Houghton *et al*., 1990) gave an atmospheric CO_2 residence time (lifetime) of 50 to 200 years as a "rough estimate." That estimate is confusingly presented as an adjustment time for a scenario with a given anthropogenic CO_2 input, and it ignores natural (sea and vegetation) CO_2 flux rates. Such estimates are analytically invalid and in conflict with the more correct explanation given elsewhere in the same IPCC report: "This means that on average it takes only a few years before a CO_2 molecule in the atmosphere is taken up by plants or dissolved in the ocean."

Some 99 percent of the atmospheric CO_2 molecules are $^{12}CO_2$ molecules containing the stable isotope ^{12}C (Segalstad, 1982). To calculate the RT of $^{12}CO_2$, Essenhigh used the 1990 IPCC data with 750 gigatons total mass atmospheric carbon and a natural input/output exchange rate of 150 gigatons of carbon per year (Houghton *et al*., 1990). The characteristic decay time (denoted by the Greek letter tau) is the former value divided by the latter value: 750 / 150 = five years. This is similar to the ~5 years found from mass balance calculations of measured atmospheric CO_2 $^{13}C/^{12}C$ carbon isotope data by Segalstad (1992), the ~5 years obtained from CO_2 solubility data by Murray (1992), and the ~5 years derived from CO_2 chemical kinetic data by Stumm and Morgan (1970).

Revelle and Suess (1957) calculated from data for the trace atmospheric molecule $^{14}CO_2$, containing the radioactive isotope ^{14}C, that the amount of atmospheric "CO_2 derived from industrial fuel combustion" would be only 1.2% for an atmospheric CO_2 lifetime of five years, and 1.73% for a CO_2 lifetime of seven years (Segalstad, 1998). Essenhigh (2009) reviewed measurements of ^{14}C from 1963 through 1995 and found the RT of atmospheric $^{14}CO_2$ is ~16 (16.3) years. He also used the ^{14}C data to determine the time value (exchange time) for variation of the concentration difference between the northern and southern hemispheres is 2.2 years for atmospheric $^{14}CO_2$. This result compares well with the observed hemispheric transport of volcanic debris leading to "the year without a summer" in 1816 in the northern hemisphere after the Tambora volcano cataclysmic eruption in Indonesia in 1815.

Sundquist (1985) compiled a large number of measured RTs of CO_2 found by different methods. The list, containing RTs for both $^{12}CO_2$ and $^{14}CO_2$, was expanded by Segalstad (1998), showing a total range for all reported RTs from one to 15 years, with most RT values ranging from five to 15 years. Essenhigh (2009) emphasizes this list of measured values of RT compares well with his calculated RT of five years for atmospheric bulk $^{12}CO_2$ and ~16 years for atmospheric trace $^{14}CO_2$. In addition, he notes the annual oscillations in the measured atmospheric CO_2 levels would be impossible without a short atmospheric residence time for the CO_2 molecules. Essenhigh further suggests the difference in atmospheric CO_2 residence times between the gaseous molecules $^{12}CO_2$ and $^{14}CO_2$ may be due to differences in the kinetic absorption and/or dissolution rates of the two different gas molecules.

Essenhigh also discusses alternative ways of expressing residence time, such as fill time, decay time, e-fold time, turnover time, and lifetime, and whether the Earth system carbon cycle is in dynamic equilibrium or nonequilibrium status. He concludes (like Segalstad, 1998) residence time is a robust parameter independent of the status of equilibrium, and that alternative expressions of the residence time give corresponding values.

It is important to compare Essenhigh's results with a paper on the same topic by Solomon *et al*.

(2009), the first author of which (Susan Solomon) co-chaired the IPCC's Working Group I addressing physical climate science. The Solomon team's paper was published after Essenhigh had submitted his manuscript to *Energy & Fuels*.

Solomon *et al*. (2009) say there is an irreversible climate change in progress due to the assimilation of CO_2 in the atmosphere, caused solely by rising anthropogenic CO_2 emissions. Their vision of the future is one in which the CO_2 level flattens out asymptotically toward infinity, giving a residence time of more than 1,000 years, without offering a definition or discussion of residence time or isotopic differences: "a quasi-equilibrium amount of CO_2 is expected to be retained in the atmosphere by the end of the millennium that is surprisingly large: typically ~40% of the peak concentration enhancement over preindustrial values (~280 ppmv)." Figure 1 of that paper shows a peak level at 1,200 ppmv atmospheric CO_2 in the year 2100, leveling off to an almost steady level of ~800 ppmv in the year 3000. It is not known how the 40% estimate was derived.

Solomon *et al*. say "this can be easily understood on the basis of the observed instantaneous airborne fraction (AF^{peak}) of ~50% of anthropogenic carbon emissions retained during their build-up in the atmosphere, together with well-established ocean chemistry and physics that require ~20% of the emitted carbon to remain in the atmosphere on thousand-year timescales [quasi-equilibrium airborne fraction (AF^{equil}), determined largely by the Revelle factor governing the long-term partitioning of carbon between the ocean and atmosphere/biosphere system]."

Solomon *et al*. (2009) neglect to consider other alternatives, however, such as that offered by Segalstad (1998), who addressed the 50 percent "missing sink" error of the IPCC, showing the Revelle evasion "buffer" factor is ideologically defined from an assumed model (atmospheric anthropogenic CO_2 increase) and an assumed preindustrial value for the CO_2 level, in conflict with the chemical Henry's Law governing the fast ~1:50 equilibrium partitioning of CO_2 between gas (air) and fluid (ocean) at Earth's average surface temperature. This CO_2 partitioning factor is strongly dependent on temperature because of the temperature-dependent retrograde aqueous solubility of CO_2, which facilitates fast degassing of dissolved CO_2 from a heated fluid phase (ocean), similar to what is experienced by heating a carbonated drink.

The correct estimate of the atmospheric residence time of CO_2 is important. The IPCC has constructed a model claiming the natural CO_2 input/output is in static balance and all CO_2 added to the atmosphere from anthropogenic carbon combustion will stay there almost indefinitely. With an anthropogenic atmospheric CO_2 residence time of 50 to 200 years (Houghton, 1990) or near-infinite (Solomon *et al*., 2009), there remains a 50 percent error (nicknamed the "missing sink") in the IPCC's model: The measured rise in the atmospheric CO_2 level is just half of that expected from the amount of anthropogenic CO_2 supplied to the atmosphere, and carbon isotope measurements invalidate the IPCC's model (Segalstad, 1992; Segalstad, 1998).

The alternative evaluation of the CO_2 residence time—giving values of about five years for the bulk of the atmospheric CO_2 molecules, as per Essenhigh's (2009) reasoning and numerous measurements with different methods—indicates CO_2 is part of a dynamic, not static, system, where about one-fifth of the atmospheric CO_2 pool is exchanged every year between different sources and sinks due to relatively fast equilibria and temperature-dependent CO_2 partitioning governed by the chemical Henry's Law (Segalstad 1992; Segalstad, 1996; Segalstad, 1998).

Starr (1993) also found the atmospheric lifetime of CO_2 is about five years, consistent with the seasonal photosynthesis swing of atmospheric CO_2 and the bomb ^{14}C decay history. The short residence time suggests anthropogenic emissions contribute only a fraction of the observed atmospheric rise and other sources, such as ocean and volcanic degassing of CO_2, need to be sought.

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2.2 Methane

What impact do global warming, the ongoing rise in the air's carbon dioxide (CO_2) content, and other contemporary environmental trends have on the atmosphere's methane (CH_4) concentration? Methane is a more powerful greenhouse gas, molecule for molecule, than is carbon dioxide. As discussed in the subsections below, there are significant forces at play that will likely produce a large negative feedback toward the future warming potential of this powerful greenhouse gas, nearly all of which are ignored or downplayed by the IPCC.

2.2.1 Atmospheric Concentrations

Atmospheric methane's contribution to anthropogenic climate forcing is estimated to be about half that of CO_2 when both direct and indirect components to its forcing are summed (see Figure 2.2.1.1). Nearly all models project atmospheric methane (CH_4) concentrations will increase for at least the next three decades, with many of the scenarios assuming a much larger increase throughout the twenty-first century. However, atmospheric methane concentrations currently lie far below the model projections in each of the four prior *Assessment Reports* of the IPCC (see Figure 2.2.1.2).

Shortly after release of the first IPCC *Assessment Report*, some researchers recognized the past two centuries' dramatic increase in atmospheric methane concentrations, sparked by the Industrial Revolution, was abruptly slowing (Dlugokencky *et al*., 1998; Francey *et al*., 1999; Lassey *et al*., 2000). Based on measurements from 43 globally distributed remote boundary-layer sites, Dlugokencky *et al*. (2003), for example, calculated global CH_4 concentration averages for the years 1984 to 2002. The results have been replotted in Figure 2.2.1.3, where the measurements are shown to fall into three groupings: initial and latter stages, to which have been fit linear regressions, and an intervening middle stage, to which has been fit a second-order polynomial.

Dlugokencky *et al*. noted the globally averaged atmospheric methane concentration "was constant at ~1751 ppb from 1999 through 2002," which suggested, in their words, that "during this 4-year period the global methane budget has been at steady state." They cautioned, "our understanding is still not sufficient to tell if the prolonged pause in CH_4 increase is temporary or permanent."

Although initially contending in 2002 (Simpson *et al*., 2002) it was "premature to believe that the CH_4 burden is ceasing to increase," four years later Simpson *et al*. (2006) acknowledged the anomalous CH_4 growth spikes to which their earlier paper had referred were indeed "superimposed on an overall slowdown of the CH_4 growth rate." The slowdown documented by Simpson *et al*. (2006) was so significant they reported "the global growth rate of atmospheric CH_4 has been near-zero for the past seven years, averaging 0.7 ± 2.6 ppbv year^{-1}." They also state "opportunities exist for still further reduc-

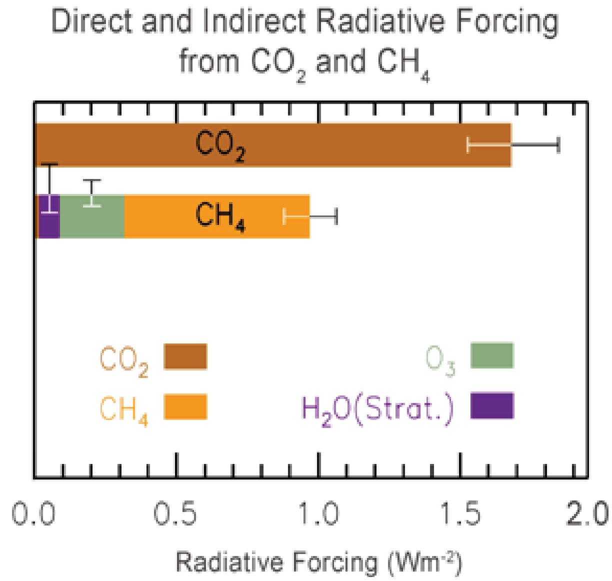

Figure 2.2.1.1. Direct and indirect radiative forcing from CO2 and CH_4, as estimated by the IPCC. Adapted from IPCC, *Climate Change 2007: The Physical Science Basis,* p. 136, FAQ 2.1, Figure 2.

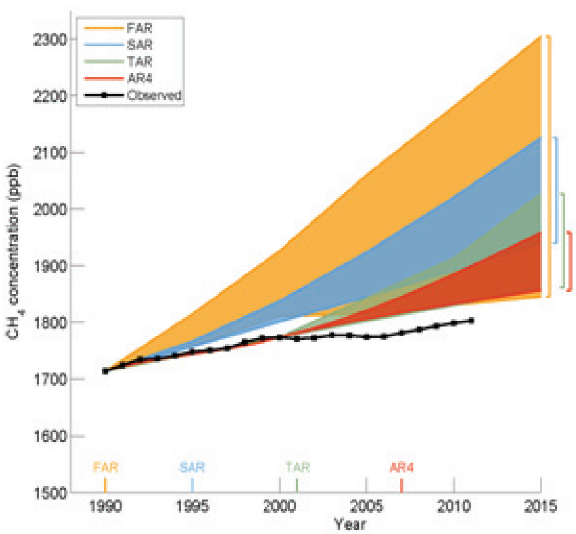

Figure 2.2.1.2. Atmospheric CH_4 projections vs observations for the first four IPCC Assessment Reports. Second Order Draft of AR5, dated October 5, 2012

tions,” noting “CH_4 levels may decrease if various CH_4 emission mitigation strategies are implemented.” They further note “the reduction of fossil fuel leakage has promise” and “because the leaking fossil fuels

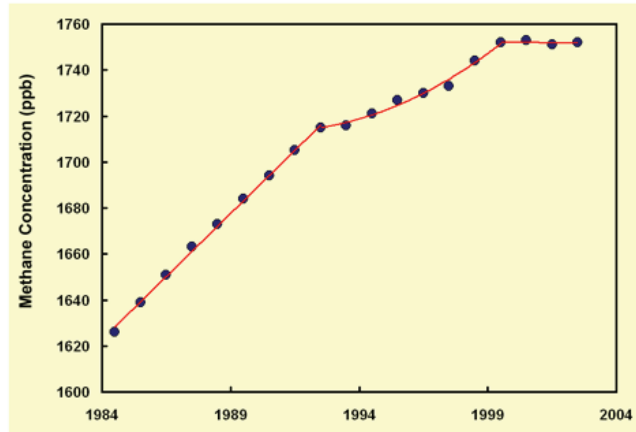

Figure 2.2.1.3. Global tropospheric methane (CH_4) concentration vs. time. Plotted from data tabulation in Dlugokencky, E.J., Houweling, S., Bruhwiler, L., Masarie, K.A., Lang, P.M., Miller, J.B., and Tans, P.P. 2003. Atmospheric methane levels off: Temporary pause or a new steady-state? *Geophysical Research Letters* **30**: 10.1029/2003GL018126.

have high value in the market, these mitigation steps can in some cases even be economically favorable.”

Simpson *et al*. (2006) point out “methane has been second only to carbon dioxide in enhanced climatic forcing from 1750 to the present.” Thus if atmospheric CH_4 levels continue to fall, rising atmospheric CO_2 levels might result in no net increase in the radiative forcing of climate. At the same time, the aerial fertilization and anti-transpirant effects of atmospheric CO_2 enrichment would grow, enhancing the efficiency of water and nutrient use by both natural and managed ecosystems. In addition, because methane is “an important source of tropospheric ozone,” as related by Simpson *et al*. (2006), the declining CH_4 concentration would alleviate much of the damage to Earth’s vegetation routinely caused by this most debilitating of air pollutants.

One year later, Khalil *et al*. (2007) combined two large atmospheric data sets to produce the unified set of data depicted in Figure 2.2.1.4, from which it is clear the rate of methane increase in the atmosphere has dropped dramatically over time. Khalil *et al.* report, “the trend has been decreasing for the last two decades until the present when it has reached near zero,” adding, “it is questionable whether human activities can cause methane concentrations to increase greatly in the future.”

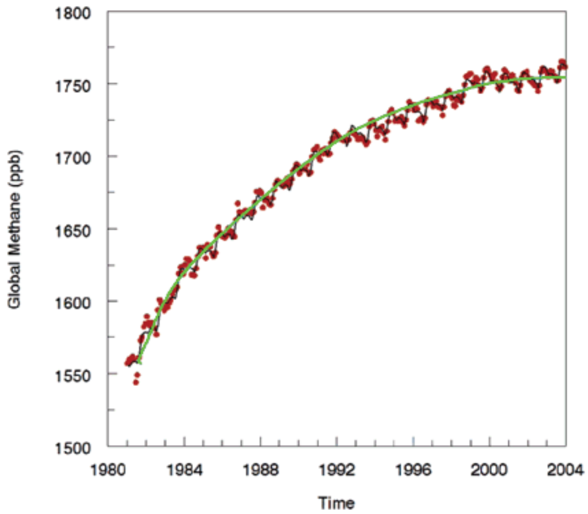

Figure 2.2.1.4. Global methane (CH_4) concentration. Adapted from Khalil, M.A.K., Butenhoff, C.L., and Rasmussen, R.A. 2007. Atmospheric methane: Trends and cycles of sources and sinks. *Environmental Science & Technology* 10.1021/ es061791t.

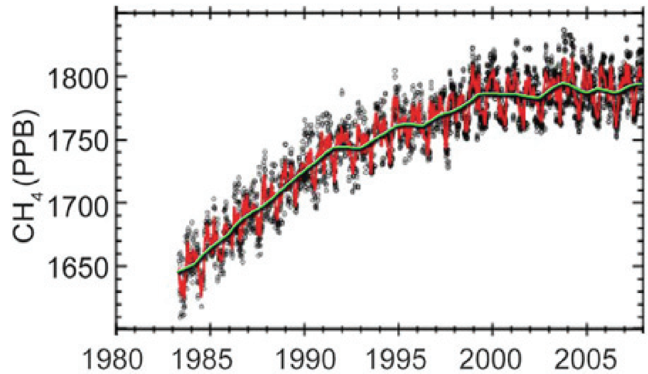

Figure 2.2.1.5. Trace gas mole fractions of methane (CH_4) as measured at Mauna Loa, Hawaii. Adapted from Schnell, R.C. and Dlugokencky, E. 2008. Methane. In: Levinson, D.H. and Lawrimore, J.H. (Eds.) *State of the Climate in 2007.* Special Supplement to the *Bulletin of the American Meteorological Society* **89**: S27.

Similar findings were reported in 2008 by Schnell and Dlugokencky, who presented an update through 2007 of atmospheric methane concentrations as determined from weekly discrete samples collected on a regular basis since 1983 at the NOAA/ESRL Mauna Loa Observatory (see Figure 2.2.1.5). Schnell and Dlugokencky note "atmospheric CH_4 has remained nearly constant since the late 1990s," the exact cause(s) of which decline "are still unclear."

In a contemporaneous study, Rigby *et al*. (2008) analyzed CH_4 data obtained from the Advanced Global Atmospheric Gases Experiment (AGAGE)—a network of five stations located in coastal regions at latitudes from 53°N to 41°S—and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), a network of eight locations around the globe that "provides an independent and complementary data set, and a wider latitudinal site distribution." The sixteen scientists report their methane measurements, which run from January 1997 to April 2008, "show renewed growth from the end of 2006 or beginning of 2007 until the most recent measurements," with the record-long range of methane growth rates hovering about zero but sometimes dropping five parts per billion (ppb) per year into the negative range, while rising near the end of the record to mean positive values of eight and 12 ppb per year for the two measurement networks.

Does this recent increase provide renewed support for the IPCC's projected increase in methane used in their model calculations of future global temperature? In a word, no—or at least not yet—for much larger increases in the methane growth rate have occurred over the past two to three decades. The most recent data from NOAA scientist Dr. Ed Dlugokencky, shown in Figure 2.2.1.6, show the global growth rate of atmospheric methane fell for nearly two decades and underwent a brief rise in 2004. That increase peaked in 2007, and since then the methane growth rate has been declining.

Only the passing of time will test the validity of atmospheric methane growth rate scenarios used by the IPCC in its projections of future climate. But if the past has taught us anything at all, it is that we do not know all we need to know about the factors that contribute to (the sources) and extract from (the sinks) methane in the atmosphere. That fact should be strikingly evident to the IPCC, whose methane projections have consistently outstretched the reality of observations in each of the prior four Assessment Reports, as illustrated earlier in Figure 2.2.1.2. The IPCC's temperature projections, which incorporate the influence of methane, are likely overinflated as well.

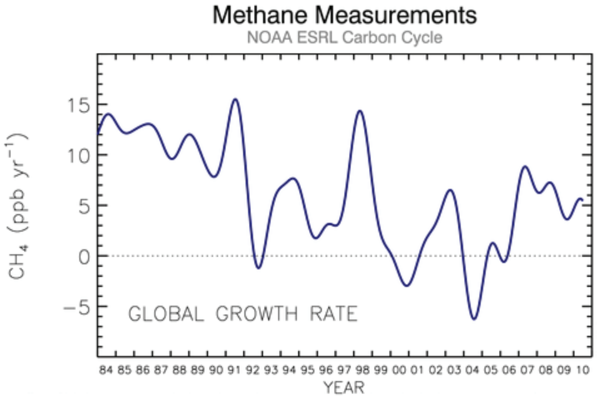

Figure 2.2.1.6. Global average growth rate of methane from the Carbon Cycle cooperative air sampling network, published by Ed Dlugokencky on the NOAA website http://www.esrl.noaa.gov/gmd/ccgg/.

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2.2.2 Emissions to the Atmosphere

2.2.2.1 Agriculture

What effect, if any, does the rise in atmospheric carbon dioxide levels have on atmospheric methane concentrations? As noted earlier, this question has important implications because, molecule for molecule, methane is a more powerful greenhouse gas than carbon dioxide. This question is considered here as it applies to methane emissions associated with agricultural operations.

Schrope *et al*. (1999) found atmospheric CO_2 enrichment might significantly reduce methane emissions associated with the production of rice. They studied rice growing in large vats filled with topsoil and placed in greenhouse tunnels maintained at atmospheric CO_2 concentrations of 350 and 700 ppm. Each of the tunnels was subdivided into four sections that provided temperature treatments ranging from ambient to as much as 5°C above ambient.

The researchers found doubling the air's CO_2 content enhanced rice biomass production by up to 35 percent above-ground and up to 83 percent below-ground. And in an unanticipated development, methane emissions from the rice grown at 700 ppm CO_2 were found to be 10 to 45 times lower than emissions from the plants grown at 350 ppm. As Schrope *et al*. describe it, "the results of this study did not support our hypothesis that an effect of both increased carbon dioxide and temperature would be an increase in methane emissions." On the contrary, they note "both increased carbon dioxide and increased temperatures were observed to produce decreased methane emissions," except for the first 2°C increase above ambient, which produced a slight increase in methane evolution from the plant-soil system.

Schrope *et al*. stated their results "unequivocally support the conclusion that, during this study, methane emissions from *Oryza sativa* [rice] plants grown under conditions of elevated CO_2 were dramatically reduced relative to plants grown in comparable conditions under ambient levels of CO_2." They replicated their experiment in a second year of sampling and obtained essentially the same results.

Four years later, a study of the same phenomenon by a different set of scientists yielded a far different result under a different set of circumstances. Inubushi *et al*. (2003) grew a different cultivar of rice in 1999 and 2000 in paddy culture at Shizukuishi, Iwate, Japan in a free-air carbon dioxide enrichment (FACE) study where the air's CO_2 concentration was increased 200 ppm above ambient. They found the extra CO_2 "significantly increased the CH_4 emissions by 38% in 1999 and 51% in 2000," which they attributed to "accelerated CH_4 production as a result of increased root exudates and root autolysis products and to the increased plant-mediated CH_4 emission because of the higher rice tiller numbers under FACE conditions." With such a dramatically different result from that of Schrope *et al*., many more studies likely will be required to clarify this relationship and determine which of these contrasting results is the more typical.

A related study was conducted by Kruger and Frenzel (2003), who note "rice paddies contribute approximately 10–13% to the global CH_4 emission (Neue, 1997; Crutzen and Lelieveld, 2001)," and "during the next 30 years rice production has to be increased by at least 60% to meet the demands of the growing human population (Cassman *et al*., 1998)." They further note "increasing amounts of fertilizer will have to be applied to maximize yields [and] there is ongoing discussion on the possible effects of fertilization on CH_4 emissions."

Kruger and Frenzel investigated the effects of N-fertilizer (urea) on CH_4 emission, production, and oxidation in rice culture in laboratory, microcosm, and field experiments conducted at the Italian Rice Research Institute in northern Italy. They report in some prior studies "N-fertilization stimulated CH_4 emissions (Cicerone and Shetter, 1981; Banik *et al*., 1996; Singh *et al*., 1996)," whereas "methanogenesis and CH_4 emission was found to be inhibited in others (Cai *et al*., 1997; Schutz *et al*., 1989; Lindau *et al*., 1990)." That is similar to the polarized findings of Schrope *et al*. and Inubushi *et al*. with respect to the effects of elevated CO_2 on methane emissions. In the mean, therefore, there may be little or no change in overall CH_4 emissions from rice fields in response to elevated CO_2 and increased N-fertilization. With respect to their own study, for example, Kruger and Frenzel report "combining our field, microcosm and laboratory experiments we conclude that any agricultural praxis improving the N-supply to the rice plants will also be favorable for the CH_4 oxidizing bacteria," noting "N-fertilization had only a transient influence and was counter-balanced in the field by an elevated CH_4 production." The implication of these findings is noted in the concluding sentence of their paper: "Neither positive nor negative consequences for the overall global warming potential could be found."

Additional understanding of CO_2-induced impacts on methane emissions from rice was gained by Cheng *et al*. (2008), who examined well-watered (flooded) and fertilized rice (*Oryza sativa* L.) plants. Plants were fumigated with air containing either 380 or 680 ppm CO_2 from the panicle formation stage at 59 days after transplanting (DAT) from seedling trays into pots within controlled-environment chambers maintained at either high (32°C) or low (22°C) night temperatures, with day temperature held constant at 32°C, until either 107 or 114 DAT. They measured the flux of methane between the pots and the atmosphere each day at 10:00 and 22:00 hours. At the conclusion of the experiment they determined the dry weight of each organ of all of the plants employed in the study.

The researchers found the extra 300 ppm of CO_2 increased CH_4 emissions by 32.2 percent in the low night temperature treatment, but by only 3.5 percent in the high night temperature treatment. They also found the elevated CO_2 increased the dry weight gained by the plants in the low night temperature treatment by 38.4 percent, but by a smaller 12.7 percent in the high night temperature treatment.

An interesting metric can be derived from these data: the ratio of the percent increase in CO_2-induced biomass production (a positive effect) to the percent increase in CO_2-induced CH_4 emissions (a negative effect) as the air's CO_2 concentration rose from 380 to 680 ppm. This benefit/cost ratio was 1.19 in Cheng *et al.*'s low-night-temperature treatment and 3.63 in their high-night-temperature treatment. Thus, from the low-night-temperature to the high-night-temperature environment, as the air's CO_2 concentration rose by 300 ppm, the benefit/cost ratio rose by a little more than 200 percent.

Because night temperatures rose significantly faster than day temperatures throughout most of the world over the past several decades, this phenomenon may have had a net two-pronged *positive* effect on the biosphere, and it could have a similar positive effect in the future, increasing the aerial fertilization effect of atmospheric CO_2 enrichment at a considerably faster relative rate than the relative rate of CO_2-induced methane emissions to the atmosphere.

Introducing their study of the subject, Qaderi and Reid (2011) write the release of aerobic methane by vegetation has been indirectly confirmed by the field studies of Braga do Carmo *et al*. (2006), Crutzen *et al*. (2006), and Sanhueza and Donoso (2006), as well as by the satellite studies of Frankenberg *et al*. (2005, 2008). In addition, they note CH_4 emissions from plants can be stimulated by higher air temperatures (Vigano *et al*., 2008; Qaderi and Reid, 2009) and water stress (Qaderi and Reid, 2009). And since "methane is the second most important long-lived greenhouse gas after carbon dioxide and is thought to be ~25 times more potent than CO_2 in its ability to act as a greenhouse gas," as they describe it, they decided to see what effect the ongoing rise in the air's CO_2 content might have on this phenomenon.

Qaderi and Reid "examined the combined effects of temperature, carbon dioxide and watering regime on CH_4 emissions from six commonly cultivated crop species: faba bean, sunflower, pea, canola, barley and wheat" in an experiment where "plants were grown from seeds in controlled-environment growth chambers under two temperature regimes (24°C day/20°C night and 30°C day/26°C night), two CO_2 concentrations (380 and 760 ppm) and two watering regimes (well watered and water stressed)," where the "plants were first grown under 24/20°C for one week from sowing, and then placed under experimental conditions for a further week," after which "plant growth, gas exchange and CH_4 emission rates were determined."

The researchers found "no detectable CH_4 from [a] control treatment (without plant tissue), indicating that CH_4 from the experimental treatments was emitted only from plant tissues." Second, they found the plants grown under higher temperature and water stress emitted more CH_4 than those grown under lower temperature and no water stress. And third, they found "elevated CO_2 had the opposite effect," "partially revers[ing]" the effects of the other two factors.

Qaderi and Reid comment, "although rising atmospheric CO_2 reduces plant CH_4 emissions, it may not fully reverse the effects of temperature and drought," which they assumed would increase in tandem with the ongoing rise in the air's CO_2 content.

Another agricultural source of methane is the fermentation of feed in the rumen of cattle and sheep. Boadi *et al*. (2004) reviewed methods for reducing CH_4 emissions from dairy cows. At the time of their review, existing mitigation strategies for reducing emissions from dairy cows included the addition of ionophores and fats to their food and the use of high-quality forages and grains in their diet, while newer mitigation strategies included "the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, [and] plant extracts (e.g., essential oils) to the diet, as well as immunization, and genetic selection of cows." The researchers provide a table of 20 such strategies, where the average maximum potential CH_4 reduction that may result from the implementation of each strategy is 30 percent or more.

Fievez *et al*. (2003) studied the effects of various types and levels of fish-oil feed additives on this process by means of both *in vitro* and *in vivo* experiments with sheep, observing a maximal 80 percent decline in the ruminants' production of methane when using fish-oil additives containing n-3-eicosapentanoic acid. The presence of condensed tannins found in certain pasture plants also can reduce methane emissions from sheep and cattle, which account for approximately 90 percent of New Zealand's methane emissions. Enriching the air with CO_2 can increase the tannin concentrations of many forage plants.

It is thus possible increasing condensed tannin concentrations in pasture crops by genetic engineering and allowing the air's CO_2 content to continue to rise could result in significant decreases in methane emissions from cattle and sheep. The outlook is also good for accomplishing this feat by including fish-oil feed additives in their diets. In addition, it is possible elevated CO_2 concentrations may lead directly to reduced methane emissions from rice culture, although more work must be done to test this hypothesis. Nevertheless, the balance of evidence suggests we can be cautiously optimistic about our agricultural intervention capabilities and their capacity to help stem the tide of Earth's historically rising atmospheric methane concentration.

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2.2.2.2 Natural Vegetation

Continuing our investigation of the effect of rising temperature, rising atmospheric carbon dioxide (CO_2)

concentrations, and other environmental trends on the atmosphere's methane (CH_4) concentration, in this section we consider methane emissions associated with natural vegetation.

Frolking and Roulet (2007) point out "throughout the Holocene, northern peatlands have both accumulated carbon and emitted methane," and "their impact on climate radiative forcing has been the net of cooling (persistent CO_2 uptake) and warming (persistent CH_4 emission)." They developed Holocene peatland carbon flux trajectories based on estimates of contemporary CH_4 flux, total accumulated peat C, and peatland initiation dates, which they used as inputs to a simple atmospheric perturbation model to calculate the net radiative impetus for surface air temperature change.

Frolking and Roulet note early in the Holocene the capture of CO_2 and emission of CH_4 by Earth's northern peatlands was likely to have produced a net warming impetus of up to +0.1 W m^{-2}. Over the following 8,000 to 11,000 years, however, they say Earth's peatlands have been doing the opposite, such that the current radiative forcing due to these atmospheric CO_2 and CH_4 perturbations represents a net cooling force on the order of -0.22 to -0.56 W m^{-2}. The impetus for global cooling due to carbon sequestration by Earth's peatlands historically has been—and currently is—significantly greater than the global warming potential produced by peatlands' emissions of methane.

Toet *et al*. (2001) point out, "only three previous published studies have assessed the impacts of O_3 on CH_4 and CO_2 fluxes in peatlands." Niemi *et al*. (2002), as they describe it, "reported that CH_4 emissions more than doubled when peatland microcosms were exposed to 100 ppb O_3 over 4–7 weeks during summer in controlled-environment chambers." In contrast, they note, "Rinnan *et al*. (2003) reported no significant effect on CH_4 emissions of a 7-week exposure of peat microcosms to 100 or 200 ppb O_3." Finally, they note "Morsky *et al*. (2008) reported that open-field exposure of boreal peatland microcosms in central Finland to a doubling of ambient O_3 concentrations caused a decrease in CH_4 emission at the end of the first growing season," but they note the decrease "was lost in the three subsequent growing seasons." Prior work on the subject thus has not provided a definitive answer to the core question of whether rising O_3 concentrations have a significant effect on methane emissions from peatlands.

In a study more reflective of reality in terms of scale, Toet *et al*. moved up in size from microcosms to mesocosms, collected from a lowland raised bog on the northern shore of Morecambe Bay, Cumbria, UK (54°13'N, 3°1'W) and subsequently placed into open-top chambers situated on a level gravel base at Newcastle University's field station (54°59'N, 1°48'W). For the next two years they observed what happened in four ambient and four O_3-enriched chambers, the latter of which had their atmospheric O_3 concentrations raised by 50 ppb for eight hours of each day during the summer period (April-early October) and by 10 ppb for eight hours of each day throughout the winter.

The researchers found "methane emissions were significantly reduced, by about 25%, by elevated ozone during midsummer periods of both years," but "no significant effect of ozone was found during the winter periods." After a lengthy discussion of their findings and those of other researchers they cite, Toet *et al*. conclude, in the final sentence of their paper, "increased O_3 could be a significant brake on the increased flux of CH_4 that is expected as these northern peatlands warm."

Davidson *et al*. (2004) report the climate of the Amazon Basin may become gradually drier due to the intensification of a number of different phenomena, including (1) less recirculation of water between the increasingly deforested region and the atmosphere, (2) more rainfall inhibition by smoke caused by increased biomass burning, and (3) a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the eastern Amazon Basin (Nepstad *et al*., 1999; see Timmermann *et al*., 1999 as well). They devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of two important greenhouse gases: nitrous oxide (N_2O) and methane (CH_4).

In the Tapajos National Forest near Santarem, Brazil, the researchers modified a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the amount of rain that reached the forest floor (throughfall) while maintaining an otherwise-similar one-hectare plot of land as a control for comparison. Prior to making this modification, they measured the gas exchange characteristics of the two plots for a period of 18 months. After initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This protocol revealed, in their words, that the "drier soil conditions caused by throughfall exclusion inhibited

N_2O and CH_4 production and promoted CH_4 consumption." They state "the exclusion manipulation lowered annual N_2O emissions by >40% and increased rates of consumption of atmospheric CH_4 by a factor of >4," which they attribute to the "direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy."

If global warming did indeed increase the frequency and/or intensity of El Niño events—which real-world data suggest is highly debatable (see Chapter 4)—the work of Davidson *et al*. (2004) suggests the anticipated drying of the Amazon Basin would initiate a strong negative feedback to warming via drying-induced reductions in the evolution of N_2O and CH_4 from its soils and a drying-induced increase in the consumption of CH_4 by its soils. Although Davidson *et al*. envisaged a more extreme second phase response, "in which drought-induced plant mortality is followed by increased mineralization of C and N substrates from dead fine roots and by increased foraging of termites on dead coarse roots" (a response that would be expected to increase N_2O and CH_4 emissions), it should be noted the projected rise in the air's CO_2 content likely would prohibit such extreme events from occurring, in light of the tendency for elevated levels of atmospheric CO_2 to increase the water use efficiency of plants, which would enable the Amazon Basin's vegetation to continue to flourish under significantly drier conditions than those of the present.

Strack *et al*. (2004) also note climate models predict increases in evapotranspiration that could lead to drying in a warming world and a subsequent lowering of water tables in high northern latitudes. This prediction stresses the importance of determining how lowered water tables will affect peatland emissions of CH_4. In a theoretical study of the subject, Roulet *et al*. (1992) calculated that for a decline of 14 cm in the water tables of northern Canadian peatlands, due to climate-model-derived increases in temperature (3°C) and precipitation (1mm/day) predicted for a doubling of the air's CO_2 content, CH_4 emissions would decline by 74 to 81 percent. In an attempt to obtain some experimental data on the subject, over the period 2001–2003 Strack *et al*. measured CH_4 fluxes to the atmosphere at different locations that varied in depth-to-water table within natural portions of a poor fen in central Quebec, Canada as well as within control portions of the fen that had been drained eight years earlier.

The Canadian scientists report, "methane emissions and storage were lower in the drained fen." The greatest reductions (up to 97 percent) were measured at the higher locations, whereas at the lower locations there was little change in CH_4 flux. Averaging the results over all locations, the researchers determined the "growing season CH_4 emissions at the drained site were 55% lower than the control site," indicating the biosphere appears to be able to resist warming influences.

In one final study of anaerobic conditions, Garnet *et al*. (2005) grew seedlings of three emergent aquatic macrophytes (*Orontium aquaticum* L., *Peltandra virginica* L., and *Juncus effusus* L.) and one coniferous tree (*Taxodium distichum* L.), all of which are native to eastern North America, in a five-to-one mixture of well-fertilized mineral soil and peat moss in pots submerged in water in tubs located within controlled environment chambers for a period of eight weeks. Concomitantly, they measured the amount of CH_4 emitted by the plant foliage, along with net CO_2 assimilation rate and stomatal conductance, which were made to vary by changing the CO_2 concentration of the air surrounding the plants and the density of the photosynthetic photon flux impinging on them.

The researchers found methane emissions from the four wetland species increased linearly with increases in both stomatal conductance and net CO_2 assimilation rate, but changes in stomatal conductance affected foliage methane flux "three times more than equivalent changes in net CO_2 assimilation," making stomatal conductance the more significant of the two CH_4 emission-controllers. They note evidence of stomatal control of CH_4 emission also has been reported for *Typha latifolia* (Knapp and Yavitt, 1995) and *Carex* (Morrissey *et al*., 1993), two other wetland plants. Since atmospheric CO_2 enrichment leads to approximately equivalent but oppositely directed changes in foliar net CO_2 assimilation (which is increased) and stomatal conductance (which is reduced) in most herbaceous plants (the type that comprise most wetlands), it can be appreciated that the ongoing rise in the air's CO_2 content should be acting to reduce methane emissions from Earth's wetland vegetation.

Shifting to studies examining aerobic conditions, Dueck *et al*. (2007) point out recent findings suggest terrestrial plants may "emit methane under aerobic conditions by an as yet unknown physiological process (Keppler *et al*., 2006), and in this way may substantially contribute to the annual global methane budget (Bousquet *et al*., 2006)," resulting in "estimated values for methane emission by terrestrial plants varying between 10 and 260 Tg yr^{-1} (Houweling *et al*., 2006; Keppler *et al*., 2006; Kirschbaum *et al*., 2006)." The 15 Dutch researchers conducted two experiments involving six plant species—*Ocimum basilicum* L. (basil), *Triticum aestivum* L. (wheat), *Zea mays* L. (maize), *Salvia officinalis* L. (sage), *Lycopersicon esculentum* Miller (tomato), and *Oenothera biennis* L. (common evening primrose)—the first three of which also were used by Keppler *et al*. (2006).

The experiments were performed in "a unique hermetically sealed plant growth chamber with a volume of 3500 liters, specifically designed for atmospheric isotope labeling," where "plants were grown hydroponically to exclude any methane production derived from anaerobic soil pockets." Dueck *et al*. reported there was no evidence for substantial aerobic methane emission by the terrestrial plants they studied, stating, "maximally," it was only "0.3% of the previously published studies." They indicate methane concentrations in continuous-flow gas cuvettes with plants "were not significantly higher than those of control cuvettes without plants," stating for both short and long terms, they "did not find any evidence of a substantial emission of methane."

Keppler *et al*.'s findings have been further challenged by other researchers. Beerling *et al*. (2008), for example, raised the C_4 plant *Zea mays* and the C_3 plant *Nicotiana tabacum* from seed for six weeks at an ambient CO_2 concentration of 400 ppm and an ambient methane concentration of 1,800 ppb, after which their leaves were studied in "a custom-built flowthrough cuvette with a sufficiently large area to allow the detection of methane emissions" via "a process gas chromatograph linked to a high-precision, high-accuracy flame ionization detector" in a controlled-environment room. The team of five U.K. researchers report "well-illuminated actively photosynthesizing *Z. mays* leaves did not, in our experimental system, emit substantial quantities of methane during repeated three-hour high irradiance episodes," and "neither did we detect methane emissions from actively respiring leaves during repeated three-hour dark periods." They additionally state "measurements with leaves of the C_3 species *N. tabacum* also failed to detect substantial aerobic methane emissions in the light when photosynthesizing with regular stomatal conductances, and in the dark when respiring."

Nisbet *et al*. (2009) "conducted further experiments on plants grown in controlled conditions" and "re-analyzed the previously published data" on the topic. The 14 researchers (13 from the U.K. and one from Sweden) demonstrated "plants do not contain a biochemical mechanism for methanogenesis" and "cannot produce methane as an end-product or by-product of their metabolism." The researchers determined "when plants transpire, any methane that is already dissolved in the water derived from the soil will be released into the atmosphere" and "under high stress conditions, such as high UV radiation, methane is released as part of the cellular breakdown process." In light of such findings, plus "a new analysis of global methane levels from satellite retrievals," Nisbet *et al*. conclude "plants are not a major source of the global methane production." They do, however, acknowledge "the role of plants in moving methane about"—that is, their importance in the global cycling of methane, but not its production.

Wang *et al*. (2009) conclude after their review of the scientific literature that "aerobic CH_4 [methane] emissions from plants may be affected by O_2 stress or any other stress leading to ROS [reactive oxygen species] production," leading the team of researchers to examine whether physical injury also would affect CH_4 emissions from plants. Their work revealed "physical injury (cutting) stimulated CH_4 emissions from fresh twigs of *Artemisia* species under aerobic conditions" and "more cutting resulted in more CH_4 emissions," as did hypoxia in both cut and uncut *Artemisia frigida* twigs.

In discussing their findings and those of previous studies that suggest, in their words, "that a variety of environmental stresses stimulate CH_4 emission from a wide variety of plant species," Wang *et al*. conclude "global change processes, including climate change, depletion of stratospheric ozone, increasing ground-level ozone, spread of plant pests, and land-use changes, could cause more stress in plants on a global scale, potentially stimulating more CH_4 emission globally," while further concluding "the role of stress in plant CH_4 production in the global CH_4 cycle could be important in a changing world."

While many factors "could" be important in stimulating methane emissions, the ongoing rise in the air's CO_2 content is countering stress-induced CH_4 emissions from plants. Although environmental stresses of all types generate highly reactive oxygenated compounds that damage plants, atmospheric CO_2 enrichment typically boosts the production of antioxidant enzymes that scavenge and detoxify those oxygenated compounds. The rise in the air's CO_2 content should have been alleviating the level of stress experienced by Earth's plants, and this phenomenon should have been reducing the rate at which the planet's vegetation releases CH_4 to the atmosphere. Perhaps that is why the rate-of-rise of the atmosphere's methane concentration has changed little in recent decades.

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2.2.3 Extraction from the Atmosphere

Methane is an important greenhouse gas, contributing roughly 20 percent of total non-H_2O radiative forcing (Menyailo and Hungate, 2003). Its atmospheric concentration is determined by the difference between how much CH_4 goes into the air (emissions) and how much comes out of it (extractions) over any particular time period. In this section we examine factors that act to extract methane from the atmosphere.

According to Prinn *et al*. (1992), one of the major means by which methane is removed from the atmosphere is via oxidation by methanotrophic bacteria in the aerobic zones of soils; the magnitude of this phenomenon is believed to be equivalent to the annual input of methane to the atmosphere (Watson *et al*., 1992). This soil sink for methane appears to be ubiquitous, as methane uptake has been observed in soils of tundra (Whalen and Reeburgh, 1990), boreal forests (Whalen *et al*., 1992), temperate forests (Steudler *et al*., 1989; Yavitt *et al*., 1990), grasslands (Mosier *et al*., 1997), arable lands (Jensen and Olsen, 1998), tropical forests (Keller, 1986; Singh *et al*., 1997), and deserts (Striegl *et al*., 1992). Forest soils—especially boreal and temperate forest upland soils (Wahlen and Reeburgh, 1996)—appear to be the most efficient (Le Mer and Roger, 2001).

Tamai *et al*. (2003) studied methane uptake rates by the soils of three Japanese cypress plantations composed of 30- to 40-year-old trees. Through all seasons of the year, they found methane was absorbed by the soils of all three sites, being positively correlated with temperature, as has been observed in several other studies (Peterjohn *et a*l., 1994; Dobbie and Smith, 1996; Prieme and Christensen, 1997; Saari *et al*., 1998). Methane absorption was even more strongly positively correlated with the C/N ratio of the cypress plantations' soil organic matter.

Based on these results, it can be surmised that CO_2-induced global warming is capable of producing two biologically mediated negative feedbacks to counter the increase in temperature: a warming-induced increase in methane uptake from the atmosphere that is experienced by essentially all soils, and an increase in soil methane uptake from the atmosphere produced by the increase in plant-litter C/N ratio that typically results from atmospheric CO_2 enrichment.

Menyailo and Hungate (2003) assessed the influence of six boreal forest species—spruce, birch, Scots pine, aspen, larch, and Arolla pine—on soil CH_4 consumption in a Siberian artificial afforestation experiment, in which the six common boreal tree species had been grown under common garden conditions for the past 30 years under the watchful eye of the staff of the Laboratory of Soil Science of the Institute of Forest, Siberian Branch of the Russian Academy of Sciences (Menyailo *et al*., 2002). The authors determined "soils under hardwood species (aspen and birch) consumed CH_4 at higher rates than soils under coniferous species and grassland." Under low soil moisture conditions, for example, the soils under the two hardwood species consumed 35 percent more CH_4 than the soils under the four conifers, while under high soil moisture conditions they consumed 65 percent more. As for the implications of these findings, Pastor and Post (1988) suggested, in the words of Menyailo and Hungate, that "changes in temperature and precipitation resulting from increasing atmospheric CO_2 concentrations will cause a northward migration of the hardwood-conifer forest border in North America." If such a shifting of species occurs, it likely will lead to an increase in methane consumption by soils and a reduction in methane-induced global warming potential—a biologically mediated negative feedback factor that is not reflected in models of global climate change.

More recently, Livesley *et al*. (2009) wrote, "soils provide the largest terrestrial carbon store, the largest atmospheric CO_2 source, the largest terrestrial N_2O [nitrous oxide] source and the largest terrestrial CH_4 sink, as mediated through root and soil microbial processes" and "a change in land use or management can alter these soil processes such that net greenhouse gas exchange may increase or decrease." As Mutuo *et al*. (2005) have noted, "intensified agricultural practices lead to a reduction in ecosystem carbon stocks, mainly due to removal of aboveground biomass as harvest and loss of carbon as CO_2 through burning and/or decomposition," such as occurs in response to tillage operations. Mutuo *et al*. further report upland forests typically consume methane, and "conversion of tropical forest soils to agriculture in general has been shown to reduce the sink strength for methane (Keller *et al*., 1990; Keller and Reiners, 1994; Steudler *et al*., 1996; Verchot *et al*., 2000)" by

50 percent or more.

Seeking to learn more about how greenhouse gas emission and absorption differ between forests and pastures, Livesley *et al*. (2009) "measured soil-atmosphere exchange of CO_2, N_2O and CH_4 in four adjacent land-use systems (native eucalypt woodland, clover-grass pasture, *Pinus radiata* and *Eucalyptus globulus* plantation) for short, but continuous, periods between October 2005 and June 2006 using an automated trace gas measurement system near Albany in southwest Western Australia." The six scientists discovered soil N_2O emissions were more than an order of magnitude greater in the pasture than in the natural and managed forests, while soil CH_4 uptake was greatest in the native woodland, even though the measured rates of uptake there were, as they describe it, "still small when compared with many other studies on native forest soils worldwide." They determined the pasture soil had the least soil CH_4 uptake (a mean of 17 percent of that in the native woodland) and that it was an occasional CH_4 source, "possibly related to its greater soil water status, greater soil nitrogen status and possible differences in soil microbial community structure." In between these two extremes, they found "afforestation with pines or eucalypts increased CH_4 uptake to 32% and 43% of that in the native woodland, respectively." With respect to CO_2, they noted "it is widely accepted that afforestation leads to an increase in carbon sequestration through tree biomass growth."

Livesley *et al*. reported their study confirmed "there is a triple greenhouse-gas benefit from afforestation of pasture systems," noting in addition to carbon sequestration via tree biomass, "there is a decrease in N_2O emissions because of lower nitrogen inputs and a tighter nutrient cycling, and an increase in CH_4 uptake by forest soils."

Guckland *et al*. (2009) conducted a two-year study of a deciduous mixed forest in the Hainich National Park, Thuringia, Germany, where they established 18 sub-plots spread throughout three types of forest and, using dark closed chambers from September 2005 to September 2007, they measured net fluxes of CH_4 every two weeks. Stand A, as they describe it, "was a single-species stand covered with European beech as the predominant tree species," while stand B "was a three-species stand with beech, ash and lime as predominant species, and stand C was covered with beech, ash, lime, hornbeam and maple as predominant species."

Guckland *et al*. report "the variation of CH_4 uptake over time could be explained to a large extent by changes in soil moisture in the upper five centimeters of the mineral soil," such that "the CH_4 uptake during the main growing period (May-September) increased considerably with decreasing precipitation rate." This finding, they write, is "in accordance with the general observation that soil moisture is the primary environmental control on CH_4 uptake in soils because it regulates methane flux into the soil through diffusion (Smith *et al*., 2000; Butterbach-Bahl and Papen, 2002; Borken *et al*., 2006)." They also report the methane flux response to soil moisture content was linear, as has been found to be the case in other studies (Dobbie and Smith, 1996; Bradford *et al*., 2001; Price *et al*., 2003). In addition, they observed "low CH_4 uptake activity during winter was further reduced by periods with soil frost and snow cover." Such findings, in the words of the three researchers, "suggest that climate change [in this case, global warming] will result in increasing CH_4 uptake rates in this region because of the trend to drier summers and warmer winters."

Carter *et al*. (2011) introduce their study of the subject by stating, "in temperate regions, climate change is predicted to increase annual mean temperature and intensify the duration and frequency of summer droughts, which together with elevated atmospheric carbon dioxide concentrations, may affect the exchange of nitrous oxide and methane between terrestrial ecosystems and the atmosphere." Working in a dry temperate heathland with a nutrient-poor sandy soil located about 50 km northwest of Copenhagen, Denmark—the vegetation of which was dominated by Scotch Heather (*Calluna vulgaris*), Wavy Hairgrass (*Deschampsia flexuosa*), and various mosses—Carter *et al*. investigated "the effects of future climatic and atmospheric conditions on the biosphere-atmosphere exchange of N_2O and CH_4."

The eight Danish researchers report warming by itself increased CH_4 uptake by about 20 percent, whereas "elevated concentrations of atmospheric CO_2 had no overall effect on the CH_4 flux, but reduced the CH_4 uptake during one measuring campaign in the winter season." They add, "in combination, the stimulating effect of warming and the episodic reducing effect of CO_2 on the CH_4 uptake resulted in a modest, but insignificant, increase in the CH_4 uptake when comparing the multifactor treatment including elevated CO_2, warming and summer drought with the ambient treatment." Carter *et al*. conclude their study "highlights the importance of evaluating climate change parameters in multifactor treatments as the response of CH_4 and N_2O flux rates to different two- and three-factor combinations may not be predicted from the responses to the individual treatments." They further state "overall, our study suggests that in the future, CH_4 uptake may increase slightly, while N_2O emission will remain unchanged in temperate ecosystems on well-aerated soils."

Zheng *et al*. (2012) reiterate that "methane is the second most important greenhouse gas contributing roughly 20% to observed global warming (IPCC, 2007)," while adding "oxidation of CH_4 in soil by methane-oxidizing bacteria (methanotrophs) currently removes 30 Tg annually from the atmosphere, which equals 5.4% of the global CH_4 sink (IPCC, 2007)." They note CH_4-eating bacteria "play a critical role in the mitigation of global warming." Exploring this potential role further, Zheng *et al*. studied the effects of a 1.2°C higher daylight temperature together with a 1.7°C higher nighttime temperature, with and without continuous concomitant grazing by adult Tibetan sheep, on methanotrophic abundance, community composition, and activity. The work was conducted at the Haibei Alpine Meadow Ecosystem Research Station of the Chinese Academy of Sciences in Qinghai Province in the northeastern corner of the Tibetan Plateau, while utilizing the infrared heating system and free-air temperature enhancement protocol developed by Kimball *et al*. (2008).

In the non-grazed treatments, Zheng *et al*. (2012) found the experimental warming increased methanotrophic abundance by approximately 93 percent, while in the grazed treatments, warming boosted methanotrophic abundance by more than twice that amount (183 percent) (see Figure 2.2.3.1).

Zheng *et al*. conclude the Tibetan Plateau "may remove more CH_4 [from the atmosphere] under future climate conditions." By inference, that will likely be the case almost everywhere, as they note "methanotrophs are widely distributed in various environments (e.g., McDonald *et al*., 2008; Op den Camp *et al*., 2009; Semrau *et al*., 2010), such as in paddy soils (Bodelier *et al*., 2000; Zheng *et al*., 2008), forest soils (Mohanty *et al*., 2007; Kolb, 2009), landfill soils (Chen *et al*., 2007; Einola *et al*., 2007; Semrau, 2011), grassland soils (Zhou *et al*., 2008; Abell *et al*., 2009), oil field soil (Zhang *et al*., 2010), and extreme thermoacidophilic environments (Dunfield *et al*., 2007; Pol *et al*., 2007; Islam *et al*., 2008)." This terrestrial effect of global warming constitutes a significant biologically induced negative feedback, independent of the additional feedbacks described above that are brought about by mere increases in the air's CO_2 concentration.

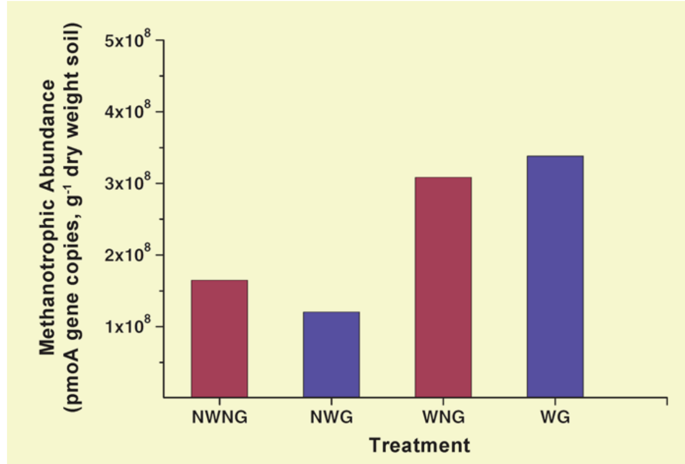

Figure 2.2.3.1. Methanotrophic abundance, expressed as the number of pmoA gene copies of methanotrophs in the soils of the four different treatments (NWNG no warming with no grazing, NWG no warming with grazing, WNG warming with no grazing, WG warming with grazing). Adapted from Zheng, Y., Yang, W., Sun, X., Wang, S.-P., Rui, Y.-C., Luo, C.-Y., and Guo, L.-D. 2012. Methanotrophic community structure and activity under warming and grazing of alpine meadow on the Tibetan Plateau. *Applied Microbiology and Biotechnology* **93**: 2193–2203.

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2.3 Nitrous Oxide

Nitrous oxide (N_2O) is an influential greenhouse gas, with a global warming potential approximately 300 times that of CO_2 on a per-molecule basis (IPCC, 2001). According to Cantarel *et al*. (2011), nitrous oxide "has shown linear increases of 0.2–0.3% per year over the last few decades, largely as a result of changes in agricultural practices and direct emissions from agricultural soils (IPCC, 2007)."

Consequently, understanding the factors that control the concentration of N_2O in the atmosphere and how the sources and sinks of N_2O vary with changes in climate and other factors is an important concern among the scientific community. This section reviews research that has been conducted on this topic, beginning with a discussion of studies examining how increases in atmospheric CO_2 might modify the release of N_2O into the atmosphere.

One of the main sources of nitrous oxide is agriculture, which accounts for almost half of N_2O emissions in some countries (Pipatti, 1997). And with N_2O originating from microbial N cycling in soil—mostly from aerobic nitrification or from anaerobic denitrification (Firestone and Davidson, 1989)—there is a concern that CO_2-induced increases in carbon input to soil, together with increasing N input from other sources, will increase substrate availability for denitrifying bacteria and may result in higher N_2O emissions from agricultural soils as the air's CO_2 content continues to rise.

In a study designed to investigate this possibility, Kettunen *et al*. (2007a) grew mixed stands of timothy (*Phleum pratense*) and red clover (*Trifolium pratense*) in sandy-loam-filled mesocosms at low and moderate soil nitrogen levels within greenhouses maintained at either 360 or 720 ppm CO_2, while measuring harvestable biomass production and N_2O evolution from the mesocosm soils over the course of three crop cuttings. This work revealed the total harvestable biomass production of *P. pratense* was enhanced by the experimental doubling of the air's CO_2 concentration by 21 percent and 26 percent, respectively, in the low and moderate soil N treatments, while corresponding biomass enhancements for *T. pratense* were 22 percent and 18 percent. In addition, the researchers found after emergence of the mixed stand and during vegetative growth before the first harvest and N fertilization, N_2O fluxes were higher under ambient CO_2 in both the low and moderate soil N treatments. It was not until the water table had been raised and extra fertilization given after the first harvest that the elevated CO_2 seemed to increase N_2O fluxes.

The four Finnish researchers conclude the mixed stand of *P. pratense* and *T. pratense* was "able to utilize the increased supply of atmospheric CO_2 for enhanced biomass production without a simultaneous increase in the N_2O fluxes," thereby raising "the possibility of maintaining N_2O emissions at their current level, while still enhancing the yield production [via the aerial fertilization effect of elevated CO_2] even under low N fertilizer additions."

Kettunen *et al*. (2007b) also grew timothy (*Phleum pratense*) in monoculture within sandy-soil-filled mesocosms located within greenhouses maintained at atmospheric CO_2 concentrations of either 360 or 720 ppm for a period of 3.5 months at moderate (standard), low (half-standard), and high (1.5 times standard) soil N supply, while they measured the evolution of N_2O from the mesocosms, vegetative net CO_2 exchange, and final above- and below-ground biomass production over the course of three harvests. The elevated CO_2 concentration increased the net CO_2 exchange of the ecosystems (which phenomenon was primarily driven by CO_2-induced increases in photosynthesis) by about 30 percent, 46 percent, and 34 percent at the low, moderate, and high soil N levels, respectively. The elevated CO_2 increased the above-ground biomass of the crop by about 8 percent, 14 percent, and 8 percent at the low, moderate, and high soil N levels, and its below-ground biomass by 28 percent, 27 percent, and 41 percent at the same respective soil N levels. Kettunen *et al*. report once again, "an explicit increase in N_2O fluxes due to the elevated atmospheric CO_2 concentration was not found."

While working at the Nevada Desert FACE facility northwest of Las Vegas, Nevada (USA), McCalley *et al*. (2011) measured soil fluxes of reactive N gases (NO, NO_y, NH_3) and N_2O in plots receiving long-term fumigation with ambient (380 ppm) and elevated (550 ppm) CO_2. These treatments were begun in April 1997; reactive N gas flux measurements were made under these conditions several years later in April 2005, July 2005, July 2006, January 2007, and March 2007, as well as after the termination of CO_2 fumigation in July 2007, October 2007, January 2008, and April 2008.

The five researchers report "long-term exposure to elevated CO_2 decreased reactive N gas emissions from Mojave Desert soils" primarily "in islands of fertility created by the dominant shrub *Larrea tridentata*," especially "in the spring and fall when recent precipitation, either natural or artificial, created soil conditions that are optimal for biological activity." Emissions of N_2O, on the other hand, were "a very small component" of gaseous N loss and were "largely insensitive to elevated CO_2." In addition, the five researchers state the greater-than-60 percent reductions in reactive N gas fluxes during periods of peak N demand imply elevated CO_2 is "increasing the retention of biologically available N during critical growth periods," a major benefit for desert ecosystems.

As reported earlier in our discussion of methane extraction from the atmosphere, Livesley *et al*. (2009) point out "soils provide the largest terrestrial carbon store, the largest atmospheric CO_2 source, the largest terrestrial N_2O source and the largest terrestrial CH_4 sink, as mediated through root and soil microbial process" and "a change in land use or management can alter these soil processes such that net greenhouse gas exchange may increase or decrease." Seeking to determine how the emission and absorption of these three greenhouse gases differ between forests and pastures, they "measured soil-atmosphere exchange of CO_2, N_2O and CH_4 in four adjacent land-use systems (native eucalypt woodland, clover-grass pasture, *Pinus radiata* and *Eucalyptus globulus* plantation) for short, but continuous, periods between October 2005 and June 2006 using an automated trace gas measurement system near Albany in southwest Western Australia."

With respect to nitrous oxide, the six scientists discovered soil N_2O emissions were more than an order of magnitude greater in the pasture than in the natural and managed forests. Given the authors' findings with respect to CO_2 and CH_4, they conclude "there is a triple greenhouse-gas benefit from afforestation of pasture systems," where in addition to carbon sequestration via tree biomass, "there is a decrease in N_2O emissions because of lower nitrogen inputs and a tighter nutrient cycling, and an increase in CH_4 uptake by forest soils."

In a different type of study, driven by the possibility that the climate of the Amazon Basin may gradually become drier due to a warming-induced increase in the frequency and/or intensity of El Niño events that have historically brought severe drought to the region, Davidson *et al*. (2004) devised an experiment to determine the consequences of the drying of the soil of an Amazonian moist tropical forest for the net surface-to-air fluxes of both N_2O and methane (CH_4).

As we reported earlier in our discussion of this study with respect to methane, the researchers modified a one-hectare plot of land covered by mature evergreen trees so as to dramatically reduce the amount of rain that reached the forest floor (throughfall), while maintaining an otherwise similar one-hectare plot of land as a control for comparison.
Prior to making this modification, the three researchers measured the gas exchange characteristics of the two plots for a period of 18 months, and after initiating the throughfall-exclusion treatment, they continued their measurements for an additional three years. This work revealed the "drier soil conditions caused by throughfall exclusion inhibited N_2O and CH_4 production and promoted CH_4 consumption." They note "the exclusion manipulation lowered annual N_2O emissions by >40 percent and increased rates of consumption of atmospheric CH_4 by a factor of >4," which they attributed to the "direct effect of soil aeration on denitrification, methanogenesis, and methanotrophy."

Other researchers also have examined the relationship between nitrous oxide emissions and soil water status. Goldberg and Gebauer (2009), for example, investigated the influence of drying and rewetting events on N_2O emissions from the soil of a mature Norway spruce forest in Northeast Bavaria, Germany. They point out "the only sink for N_2O considered in global models is the destruction of atmospheric N_2O in the stratosphere through photolysis and photooxidation (IPCC, 2007)." Citing the 2007 IPCC report, they note "soils have been identified as the main sources for atmospheric N_2O."

To learn more about the emission of N_2O from wet vs. dry soils, Goldberg and Gebauer induced an artificial summer drought of 46 days duration (which was accompanied by a natural drought) via throughfall exclusion (TE) that was provided by special roof installations, which they followed with an experimental rewetting of 66 mm over two days, during which periods (and before and after them) they closely monitored N_2O fluxes from the soils of the TE and unaltered control (C) plots that were exposed to the elements.

The two researchers write, "before the drought, both the C and TE plots showed slightly positive N_2O fluxes from the soil to the atmosphere," in harmony with the sentiment of the IPCC. During the drought, on the other hand, "the soil of both the throughfall exclusion and control plots served as an N_2O sink," contrary to what might have been expected in light of IPPC statements. They state, "the sink strength of the throughfall exclusion plots was doubled compared with the control plots." Rewetting "turned the soil into a source for atmospheric N_2O again," but "it took almost four months to turn the cumulative soil N_2O fluxes from negative (sink) to positive (source) values." Goldberg and Gebauer conclude, "long drought periods can lead to drastic decreases of N_2O fluxes from soils to the atmosphere or may even turn forest soils temporarily to N_2O sinks," which may in some places persist for years at a time. It is also possible that over the entire terrestrial surface of the planet, the net result is that "soils are the main sources for atmospheric N_2O," as stated by the IPCC. Nevertheless, the two scientists conclude that what they call an unbalanced global N_2O budget "underlines the likelihood of a hitherto unconsidered sink function of soils."

In combining the effects of soil water status and atmospheric CO_2 on N_2O emissions, Welzmiller *et al*. (2008) measured N_2O and denitrification emission rates in a C_4 sorghum [*Sorghum bicolor* (L.) Moench] production system with ample and limited flood irrigation rates under free-air CO_2 enrichment (seasonal mean = 579 ppm) and control (seasonal mean = 396 ppm) conditions during the 1998 and 1999 summer growing seasons at the experimental FACE site near Maricopa, Arizona (USA). They found "elevated CO_2 did not result in increased N_2O or N-gas emissions with either ample or limited irrigation," which they describe as being "consistent with findings for unirrigated western U.S. ecosystems reported by Billings *et al*. (2002) for Mojave Desert soils and by Mosier *et al*. (2002) for Colorado shortgrass steppe." Welzmiller *et al*. say their results suggest "as CO_2 concentrations increase, there will not be major increases in denitrification in C_4 cropping environments such as irrigated sorghum in the desert southwestern United States," which further suggests there will not be an increased impetus for global warming due to this phenomenon.

Adding temperature to the mix, Cantarel *et al*. (2011) monitored N_2O fluxes in an *in situ* ecosystem manipulation experiment simulating the climate predicted for the study area (an upland temperate grassland in the French Massif Central region), making use of the Clermont Climate Change Experiment facility, where Bloor *et al*. (2010) were conducting "a long-term grassland study of multiple climate changes applied in an additive experimental design." Over a two-year period, they monitored N_2O fluxes under conditions "simulating the climate predicted for the study area in 2080 (3.5°C temperature increase, 20% reduction in summer rainfall and atmospheric CO_2 levels of 600 ppm)."

"Overall," as the four researchers describe the results of their study, "experimental warming had a positive effect on the annual N_2O emissions." However, and "contrary to expectations," as they put it, "combined summer drought and warming had no significant effect on mean N_2O fluxes recorded at any time," nor did "elevated CO_2 in combination with warming and drought."

Also writing in 2011, Carter *et al*. (2011) note "in temperate regions, climate change is predicted to increase annual mean temperature and intensify the duration and frequency of summer droughts, which together with elevated atmospheric carbon dioxide concentrations, may affect the exchange of nitrous oxide (N_2O) and methane (CH_4) between terrestrial ecosystems and the atmosphere." Working in a dry, temperate heathland with a nutrient-poor sandy soil located about 50 km northwest of Copenhagen, Denmark—the vegetation of which was dominated by Scotch Heather (*Calluna vulgaris*), Wavy Hairgrass (*Deschampsia flexuosa*), and various mosses—Carter *et al*. set out to investigate "the effects of future climatic and atmospheric conditions on the biosphere-atmosphere exchange of N_2O and CH_4."

With respect to N_2O emissions (we reported their results with respect to methane earlier), the researchers found "as single experimental factors, elevated CO_2, temperature and summer drought had no major effect on the N_2O fluxes, but the combination of CO_2 and warming stimulated N_2O emission, whereas the N_2O emission ceased when CO_2 was combined with drought." Carter *et al*. conclude their study "highlights the importance of evaluating climate change parameters in multifactor treatments as the response of CH_4 and N_2O flux rates to different two- and three-factor combinations may not be predicted from the responses to the individual treatments." They add, "overall, our study suggests that in the future, CH_4 uptake may increase slightly, while N_2O emission will remain unchanged in temperate ecosystems on well-aerated soils."

The research reviewed here thus suggests concerns about additional global warming arising from enhanced N_2O emissions from agricultural soils in a CO_2-enriched atmosphere of the future are not well founded.

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2.4 Clouds

Understanding how Earth's clouds respond to anthropogenic-induced perturbations of the atmosphere is of paramount importance in determining the impact of the ongoing rise in the air's CO_2 content on global climate. Both naturally occurring and manmade aerosols have a strong influence on cloud albedo (solar reflectance) and cloud cover, with a global mean thermal forcing estimated to be of approximately the same magnitude as that of mankind's production of greenhouse gases, but of opposite sign.

The following subsections present brief reviews of a number of scientific papers that address these important subjects. Additional information can be found in related subjects treated in this volume, including the inadequacies of climate models in dealing with clouds and the climatic influence of aerosols (see Chapter 1).

2.4.1 Albedo

Perhaps the best-known imputed impact of mankind on climate is the enhancement of the atmosphere's greenhouse effect said to be produced by the carbon dioxide released into the atmosphere by the burning of fossil fuels such as coal, gas, and oil. There are, however, several other ways in which human activities are believed to influence Earth's climate, and many of these phenomena tend to *cool* the globe, primarily by enhancing its albedo, or reflectance of incoming solar radiation.

Ferek *et al*. (1998), for example, observed an increase in the reflectance of solar radiation from clouds exposed to the airborne effluents of ships, while Capaldo *et al*. (1999) determined this phenomenon creates a significant cooling influence over water surfaces in the Northern and Southern Hemispheres. Facchini *et al*. (1999) report organic solutes evolving from agricultural/industrial regions tend to enhance cloud reflectance over land.

Charlson *et al*. (2001) note clouds droplets "are the most important factor controlling the albedo (reflectivity) and hence the temperature of our planet," and manmade aerosols "have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases." Even a small change in cloud properties could determine whether the combined influence of anthropogenic activities results in a net warming or cooling of the planet.

The results of several empirical studies led Charlson *et al*. to conclude the anthropogenic impetus for cooling "may be even larger than anticipated." He and his colleagues point out the early IPCC assessments of the situation "do not include the combined influences of some recently identified chemical factors, each of which leads to additional negative forcing (cooling) on top of that currently estimated." They write, "It has recently become clear that soluble gases, slightly soluble solutes [aerosols], and surface tension depression by organic substances also influence the formation of cloud droplets." The ways in which mankind's activities influence these processes tend to produce extra cloud cooling power that is nowhere to be found in early IPCC analyses of cloud effects on climate.

Consider, for example, the original hypothesis developed by Charlson *et al*. (1987), which has inspired literally hundreds of subsequent confirmatory studies, wherein biology plays an integral role in mitigating global warming. This scenario begins with an initial impetus for warming that stimulates primary production in marine phytoplankton, which results in the production of more copious quantities of dimethylsulphoniopropionate (DMSP), which leads to the evolution of greater amounts of dimethyl sulphide (DMS) in the surface waters of the world's oceans. The DMS diffuses into the atmosphere, where it is oxidized, which leads to the creation of acidic aerosols that function as cloud condensation nuclei. Those nuclei create more and brighter clouds of higher albedo, which reflect more incoming solar radiation back to space, which cools the planet and thereby counters the initial impetus for warming.

Simo and Pedros-Alio (1999) added even more complexity to this scenario by describing a number of short-term photo-induced (and, therefore, mixing-depth mediated) influences on several complex physiological phenomena manifest in marine phytoplankton, as well as longer-term variations in vertical mixing that influence planktonic succession and food-web structure. Ayers and Gillett (2000) summarized empirical evidence in support of Charlson *et al*.'s hypothesis obtained from data collected at Cape Grim, Tasmania since 1988, as well as from what has been reported in prior studies of the subject. They too conclude there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer."

Sciare *et al*. (2000) made continuous measurements of atmospheric DMS concentration and a number of environmental parameters from 1990 to 1999 at Amsterdam Island in the southern Indian Ocean, finding a clear seasonal variation with a factor of 20 difference in amplitude between the maximum atmospheric DMS concentration in austral summer and the minimum in austral winter. The DMS anomalies were found to be "closely related to sea surface temperature anomalies, clearly indicating a link between DMS and climate changes." They found a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50 percent on a monthly basis, providing what they called a "very important" albedo-moderated negative feedback on the original impetus for warming. (DMS will be discussed more thoroughly later in this chapter.)

In addition to DMS, there is COS, carbonyl sulfide, which operates in a somewhat similar albedo-enhancing fashion over land. COS is the most stable and abundant reduced sulfur gas in the atmosphere and a major player in determining Earth's radiation balance. After making its way into the stratosphere, it can be photo-dissociated, as well as oxidized, to form SO_2, which is typically converted to sulfate aerosol particles that are highly reflective of incoming solar radiation and, therefore, have the capacity to significantly cool Earth. Like DMS, COS is heavily influenced by planetary biology.

In a study of COS uptake by a lichen species found in an open-oak woodland in central California, Kuhn and Kesselmeier (2000) observed the rate of absorption of COS from the atmosphere by this species declined dramatically once air temperature rose above 25°C. Thus, when temperatures begin to become uncomfortably warm for this and many other species of plants (and animals), more COS remains in the air, which increases the potential for more of it to make its way into the stratosphere, where it can be converted into sulfate aerosol particles that can reflect more incoming solar radiation back to space and thereby cool Earth. Since the consumption of COS by lichens is under the physiological control of carbonic anhydrase—the key enzyme for COS uptake in all higher plants, algae, and soil organisms—one could expect this phenomenon to be generally operative over much of the planet, which it is. This biological "thermostat" may be powerful enough to define an upper limit above which the surface air temperature of Earth may be restricted from rising, even when changes in other forcing factors, such as greenhouse gases, produce a substantial impetus for warming. (COS will be discussed more completely later in this chapter.)

That several of the above-described phenomena, as well as others yet to be elucidated, may be occurring at the present time is suggested by the study of Herman *et al*. (2001), who used satellite data to determine changes in radiation reflected back to space over the period 1979 to 1992. Their data indicate "there have been increases in reflectivity (cloudiness) poleward of 40°N and 30°S, with some smaller but significant changes occurring in the equatorial and lower middle latitudes." And they state the overall long-term effect is for an increase in radiation reflected back to space of 2.8 W m^{-2} per decade, from which they conclude, "there is a likely cooling effect" provided "by changes in the amount of snow/ice, cloudiness, and aerosols."

One year later, Chou *et al*. (2002) analyzed aerosol optical properties retrieved from the satellite-mounted Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and used them in conjunction with a radiative transfer model of the planet's atmosphere to calculate the climatic effects of aerosols over Earth's oceans. They found "aerosols reduce the annual-mean net downward solar flux by 5.4 W m^{-2} at the top of the atmosphere, and by 5.9 W m^{-2} at the surface." During the large Indonesian fires of September-December 1997, however, the radiative impetus for cooling at the top of the atmosphere was more than 10 W m^{-2}, and it was more than 25 W m^{-2} at the surface of the sea in the vicinity of Indonesia.

The magnitude of the radiative warming impetus predicted at the start of the global warming controversy to occur in response to a nominal doubling of the air's CO_2 content is about 4 W m^{-2}, less than what researchers have found to be the radiative cooling effect of atmospheric aerosols. Thus over the majority of the planet's surface, the radiative cooling influence of atmospheric aerosols (many of which are produced by anthropogenic activities) likely prevails, suggesting a probable net anthropogenic-induced climatic signal that must be very close to zero and nowhere near capable of producing what the IPCC refers to as the unprecedented warming of the twentieth century.

Breon *et al*. (2002) assessed the effects of atmospheric aerosols around the globe on cloud microphysics via data on aerosol concentration and cloud droplet radii obtained from the polarization and directionality of the Earth reflectances (POLDER) instrument on the Advanced Earth-Observing Satellite (ADEOS), which began operation on 30 October 1996 and ended on 30 June 1997. In their words, the study's results "clearly demonstrate a significant impact of aerosols on cloud microphysics." As aerosol concentrations increased, cloud droplet radii decreased, which should produce a cooling influence due to the greater albedo generally associated with smaller cloud droplets. The researchers also determined "the bulk of the aerosol load originates from slash-and-burn agriculture practices and from highly polluted areas," such that "a large fraction of the observed aerosol effect on clouds is probably of anthropogenic origin."

Although Breon *et al*. were unable to quantify the degree of cooling provided by the presence of the aerosols they studied, they nevertheless concluded this anthropogenic counterforce to the warming impetus provided by the ongoing rise in the air's CO_2 content is "significant and occurs on a global scale."

Several natural and anthropogenic-induced negative feedbacks clearly are capable of maintaining the climate of the globe within a temperature range conducive to the continued well-being of all forms of life on Earth. Many of these feedbacks have yet to receive the attention they merit from the IPCC.

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2.4.2 Cloud Cover

In addition to cloud albedo, the reaction of cloud cover to anthropogenic-induced changes in the atmosphere is an important part of the discussion over how climate will be affected by an ongoing rise in the air's carbon dioxide content. Here we review scientific papers that address this topic.

Ferek *et al*. (1998) determined cloud condensation nuclei in the airborne effluents of ships off the west coast of the United States were responsible for producing ship tracks—brighter and more persistent streaks in the overlying layer of natural and less-reflective cloud, both of which exert a cooling influence during daylight hours. Similarly, based on what is known about the properties of the aerosols responsible for jet aircraft contrails, Meerkotter *et al*. (1999) suggest the presence of such contrails tends to cool Earth's surface during daylight hours but warm it at night. They also note aircraft emissions may cause additional indirect climate forcing by changing the particle size of natural cirrus clouds, concluding "this indirect forcing may be comparable to the direct forcing due to additional contrail cloud cover."

Boucher (1999) and Nakanishi *et al*. (2001) both find aircraft-induced increases in high-cloud amount may also have a warming effect, although Charlson *et al*. (2001) contend the net effect of all anthropogenic-produced aerosols averaged over the globe is a cooling.

Facchini *et al*. (1999) studied the effects of atmospheric solutes collected from cloud water in the Po Valley of Italy. They found water vapor was more likely to form on its organic-solute-affected aerosols of lower surface tension—as opposed to the less-organic-solute-affected aerosols of the natural environment with their higher surface tension—creating more, smaller, and therefore more highly reflective cloud droplets, which tend to cool the local environment. They also observed the organic fractions and concentrations of the aerosols they studied were similar to those found in air downwind of other large agricultural/industrial regions, hinting at the likely widespread occurrence of this human-induced cooling influence.

Studying this phenomenon several years earlier, Kulmala *et al*. (1993) noted "it is likely that the smaller droplet size will decrease precipitation so that the clouds will have a longer lifetime." In addition, they observed "cloud formation can take place at smaller saturation ratios of water vapor" in the presence of organic-solute-affected aerosols, suggesting clouds will be able to form earlier and in places where they would not otherwise form. In response to this particular type of anthropogenic effluent, therefore, cloud lifetimes expand at both ends—they are born earlier and die later, so to speak.

How significant are these phenomena? Leaitch *et al*. (1992) conclude the increased radiative cooling power due only to the increase in cloud albedo that results from pollution-induced increases in cloud droplet concentration averages about 2 W m^{-2} over North America, about half the radiative warming power typically predicted to accompany a nominal doubling of the air's CO_2 content. Adding the impact of increased cloud cover likely would make the overall effect considerably greater.

Satheesh and Ramanathan (2000) measured the clear-sky radiative consequences of the December-to-April northeastern low-level monsoonal flow of air that transports sulphates, nitrates, organics, soot, and fly ash (among other anthropogenically produced substances) from the Indian subcontinent and southern Asia thousands of kilometers over the north Indian Ocean and as far south as 10°S latitude. They found the "mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to 30 W m^{-2}," which Schwartz and Buseck (2000) point out is "three to seven times as great as global average longwave (infrared) radiative forcing by increases in greenhouse gases over the industrial period … but opposite in sign."

This finding was somewhat tempered by the study of Ackerman *et al*. (2000), who suggest the large cooling effect likely was counterbalanced by a simultaneous reduction in cloud cover. But in an analysis of a long-term study of real-world data, Norris (2001) proved that suggestion to be wrong, reaffirming the overall implications of the Satheesh and Ramanathan study.

Norris reasoned that if the conclusion of Ackerman *et al*. was correct, the great increase in anthropogenic aerosol emissions from southern and southeast Asia over the past half-century should have significantly decreased the low-level cloud cover over the northern Indian Ocean during this period. A test of this idea with data from the Extended Edited Cloud Report Archive, however, revealed daytime low-level cloud cover over this part of the world in fact increased, and it did so in both the Northern and Southern Hemispheric regions of the study area and at essentially all hours of the day.

Croke *et al*. (1999) determined the mean cloud cover of three regions of the United States (coastal southwest, coastal northeast, and southern plains) rose from 35 percent to 47 percent from 1900 to 1987, while global mean air temperature rose by approximately 0.5°C. Similarly, Chernykh *et al*. (2001) determined global cloud cover rose by nearly 6 percent between 1964 and 1998. These observations suggest Earth's hydrologic cycle does indeed tend to moderate the thermal effects of any impetus for warming and, as noted by the latter authors, is "consistent with the decrease in diurnal temperature range evident over most of the globe."

Another way by which clouds tend to stabilize Earth's climate was suggested by Sud *et al*. (1999). Based on data from the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment, these investigators found deep convection in the tropics acts as a thermostat to keep vacillation of sea surface temperature (SST) within a rather narrow range. Starting at the low end of the range, the tropical ocean acts as a net receiver of energy and warms. Soon thereafter, however, the cloud-base airmass is charged with the moist static energy needed for clouds to reach the upper troposphere, and the cloud cover thus formed reduces the amount of solar radiation received at the sea surface, while its cool and dry downdrafts also tend to promote surface cooling. This "thermostat-like control," as Sud *et al*. put it, tends to "ventilate the tropical ocean efficiently and help contain the SST between 28–30°C."

Lindzen *et al*. (2001) described another mechanism through which tropical ocean temperatures may be constrained by cloud-mediated phenomena. Based on upper-level cloudiness data obtained from the Japanese Geostationary Meteorological Satellite and SST data obtained from the National Centers for Environmental Protection, these researchers determined the cloudy moist region of the eastern part of the tropical western Pacific "appears to act as an infrared adaptive iris that opens up and closes down the regions free of upper-level clouds, which more effectively permit infrared cooling, in such a manner as to resist changes in tropical surface temperature." The strong inverse relationship they found between upper-level cloud area and mean SST was determined to be sufficient to "more than cancel all the positive feedbacks in the more sensitive current climate models."

Plant life also plays an important role in stabilizing climate. The pioneering paper of Charlson *et al*. (1987), for example, describes how an initial SST increase leads to increased phytoplanktonic productivity in Earth's oceans, which leads to a greater sea-to-air flux of dimethyl sulfide (DMS), which undergoes a gas-to-particle conversion that leads to greater numbers of cloud condensation nuclei that create more and brighter clouds that reflect more incoming solar radiation back to space, thereby countering the initial impetus for warming. Subsequently, Ayers and Gillett (2000) reviewed what had been learned in the following years, concluding "major links in the feedback chain proposed by Charlson *et al*. (1987) have a sound physical basis," additionally noting there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

Further support for the powerful negative feedback loop is provided by Simo and Pedros-Alio (1999), who studied the effect of the depth of the surface mixing-layer on DMS production. (For a more complete discussion of DMS, see the section on Dimethylsulfide, this chapter.)

Although studies of real-world phenomena continue to clarify the workings of the planet's climate system and improve our understanding of it, computer models have a difficult time capturing the system's complexities. Groisman *et al*. (2000), for example, evaluated the ability of several climate models to reproduce mean daily cloud-temperature relations at different times of year. Although most models did a good job in the cold part of the year, "large discrepancies between empirical data and some models are found for summer conditions." The overall cloud effect on summer near-surface air temperature computed by one of the models was of the wrong sign.

In another study, Gordon *et al*. (2000) examined the response of a coupled general circulation model of the atmosphere to quasi-realistic specified marine stratocumulus clouds and compared the results to what they obtained from their model when operating in its normal mode, which fails to adequately express the presence of the clouds and their effects. When they removed the low clouds, as occurs in the model's normal application, the sea surface temperature warmed by fully 5.5°C.

Two years later, two data-based studies published in *Science*—Chen *et al*. (2002) and Wielicki *et al*. (2002)—revealed what Hartmann (2002) called a pair of "tropical surprises." The first of the seminal discoveries was the finding of both Chen *et al*. and Wielicki *et al*. that the amount of thermal radiation emitted to space at the top of the tropical atmosphere increased by about 4 W m^{-2} between the 1980s and the 1990s; the second was that the amount of reflected sunlight decreased by 1 to 2 W m^{-2} over the same period, with the net result that more total radiant energy exited the tropics in the latter decade.

These changes were significant. The measured thermal radiative energy loss at the top of the tropical atmosphere, for example, was of the same magnitude as the thermal radiative energy gain generally predicted for a doubling of the air's CO_2 content. Yet as Hartman noted, "only very small changes in average tropical surface temperature were observed during this time." So what went wrong—or more correctly, what went right?

For one, the competing change in solar radiation reception driven by changes in cloud cover allowed more solar radiation to reach the surface of Earth's tropical region and warm it. These changes were produced by what Chen *et al*. determined to be "a decadal-time-scale strengthening of the tropical Hadley and Walker circulations." Moreover, the past quarter-century's slowdown in the meridional overturning circulation of the upper 100 to 400 meters of the tropical Pacific Ocean, recently reported by

McPhaden and Zhang (2002), would have promoted tropical sea surface warming by reducing the rate of supply of relatively colder water to the region of equatorial upwelling.

These observations provide several new phenomena for the models to replicate as a test of their ability to properly represent the real world. McPhaden and Zhang note, for example, the meridional overturning circulation of the upper Pacific Ocean provides "an important dynamical constraint for model studies that attempt to simulate recent observed decadal changes in the Pacific." If the climate models cannot reconstruct this simple wind-driven circulation, it is difficult to be confident in their projections.

In an application of this principle, Wielicki *et al.* (2002) tested the ability of four state-of-the-art climate models and one weather assimilation model to reproduce the observed decadal changes in top-of-the-atmosphere thermal and solar radiative energy fluxes that occurred over the past two decades. No significant decadal variability was exhibited by any of the models, and all were unable to reproduce even the cyclical seasonal change in tropical albedo. The administrators of the test conclude "the missing variability in the models highlights the critical need to improve cloud modeling in the tropics so that prediction of tropical climate on interannual and decadal time scales can be improved." Hartmann is more candid in his scoring of the test, saying it indicates "the models are deficient." He notes, "if the energy budget can vary substantially in the absence of obvious forcing," as it did over the prior two decades, "then the climate of Earth has modes of variability that are not yet fully understood and cannot yet be accurately represented in climate models." (Additional discussion of climate models' treatment of clouds can be found in Chapter 1.)

Fu *et al.* (2002) and Hartmann and Michelsen (2002) continued to chip away at the adaptive infrared iris concept of Lindzen *et al.* (2001). Fu *et al.* argue "the contribution of tropical high clouds to the feedback process would be small since the radiative forcing over the tropical high cloud region is near zero and not strongly positive," while also claiming to show water vapor and low cloud effects are overestimated by Lindzen *et al.* by at least 60 percent and 33 percent, respectively. Fu and his colleagues obtained a feedback factor in the range of -0.15 to -0.51, compared to Lindzen *et al.*'s larger negative feedback factor of -0.45 to -1.03.

Chou *et al.* (2002) responded, suggesting Fu *et al.*'s approach of specifying longwave emission and cloud albedos "appears to be inappropriate for studying the iris effect." They note, "thin cirrus are widespread in the tropics and … low boundary clouds are optically thick," and "the cloud albedo calculated by [Fu *et al.*] is too large for cirrus clouds and too small for boundary layer clouds," so that "the near-zero contrast in cloud albedos derived by [Fu *et al.*] has the effect of underestimating the iris effect." Chou *et al.* ultimately agreed Lindzen *et al.* "may indeed have overestimated the iris effect somewhat, though hardly by as much as that suggested by [Fu *et al.*]."

Two years later, Minnis *et al.* (2004) analyzed surface-based measurements of cirrus coverage (CC) for different parts of the world for the period 1971–1995 while employing similar measurements obtained from the International Satellite Cloud Climatology Project (ISCCP) for 1984–1996 as a consistency check. The linear trends they derived from the data were input to a relationship between changes in cirrus amount and surface temperature (derived from a general circulation model of the atmosphere) in order to calculate their climatic impact over the United States.

Minnis *et al.* report "values of CC increased over the United States, the North Atlantic and Pacific, and Japan, but dropped over most of Asia, Europe, Africa, and South America," noting "the largest concentrated increases occurred over the northern Pacific and Atlantic and roughly correspond to the major air traffic routes." Their U.S. temperature assessment additionally indicates "the cirrus trends over the United States are estimated to cause a tropospheric warming of 0.2°–0.3°C per decade, a range that includes the observed tropospheric temperature trend of 0.27°C per decade between 1975 and 1994." Those results suggest nearly all of the surface warming observed over the United States between 1975 and 1994, which they reported to be 0.54°C, may have been due to aircraft-induced increases in cirrus cloud cover and not the increase in the air's CO_2 content over that period.

Harrison and Stephenson (2005) reasoned that because the net global effect of clouds is cooling (Hartmann, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, just as local overcast conditions can do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF) measured daily at 0900 UT at Whiteknights, Reading (UK) in 1997–2004 with the traditional subjective determination of cloud amount made simultaneously by a human observer as well as with daily average temperature. They then compared the DF measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux.

Their work revealed "across the UK, on days of high cosmic ray flux (above 3600×10^2 neutron counts per hour, which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by 19% ± 4%, and (ii) the diffuse fraction increases by 2% ± 0.3%." In addition, they found "during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction," and they note the latter of these observations indicates diffuse radiation changes are, indeed, "unambiguously due to cosmic rays." They further report, "at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR" and suggest the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima. They note, "this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al*., 2003) which neglect a cosmic ray effect." In addition, although the effect they detect is small, they state it is "statistically robust" and the cosmic ray effect on clouds likely "will emerge on long time scales with less variability than the considerable variability of daily cloudiness."

The following year, Palle *et al*. (2006) used the most up-to-date cloud cover data from the International Satellite Cloud Climatology Project and, following the protocols of Palle *et al*. (2004), derived globally averaged albedo anomalies and related solar radiative forcing anomalies experienced by Earth over the prior two decades. In addition, the four researchers explored the effects on total radiative forcing (solar plus thermal) of observed changes in the amounts of low-, high-, and mid-level clouds that occurred between 2000 and 2004.

Between 1985 and 2000, Palle *et al*. calculated, the flux of solar radiation absorbed by the Earth-atmosphere system rose by about 8 W m^{-2} in response to an observed decline in total cloud amount. Thereafter, total cloud amount began to rise, but because of a concomitant redistribution of cloud types (an increase in high- and mid-level clouds that tend to warm the planet, and a decrease in low-level clouds that tend to cool the planet), they conclude the positive radiative forcing trend experienced between 1985 and 2000 may have continued to the time of the writing of their paper, even in the face of an increasing total cloud amount.

Palle *et al*. note the increase in radiative forcing produced by the increasing atmospheric concentrations of all greenhouse gases since 1850 was roughly 2.5 W m^{-2}. Compared to the increase in radiative forcing that may have been experienced between 1985 and 2005 as a result of observed changes in total cloud amount and the fractions of clouds located at different elevations (~11 W m^{-2}, according to the data and analyses of Palle *et al*.), the 20-year change in radiative forcing due to CO_2 alone would have been truly minuscule, suggesting the angst manifest over anthropogenic CO_2 emissions may be misplaced. And if a radiative forcing of ~11 W m^{-2} raised mean global air temperature by only a fraction of a degree, as occurred between 1985 and 2005, it would appear Earth's climate is much less responsive to changes in radiative forcing than the IPCC and most climate modelers claim it to be.

One additional study merits discussion here. Based on approximately 185 million synoptic weather observations obtained from 5,400 stations worldwide, covering all continents and many islands, Warren *et al*. (2007) developed separate day and night histories of cloud amount for nine cloud types for the 26-year period 1971–1996. This work revealed, "there are large regional changes in cloud-type amounts, and significant changes in the global averages of some cloud types." More specifically, they state "the time series of total-cloud-cover anomalies for individual continents show a large decrease for South America, small decreases for Eurasia and Africa, and no trend for North America." They also observe "the zonal average trends of total cloud cover are positive in the Arctic winter and spring, 60°–80°N, but negative in all seasons at most other latitudes." In addition, they state "night trends agree with day trends for total cloud cover and for all cloud types except cumulus," and "cirrus trends are generally negative over all continents." They found these changes "compensate each other to result in only a small trend of global average land cloud cover, -0.7% $decade^{-1}$." In addition, they note "this small negative trend is further compensated by a small positive trend over the ocean of +0.4% $decade^{-1}$ (Norris, 1999), resulting in almost no trend for global average cloud cover over the past few decades."

Although Warren *et al*. acknowledged the significance of changes in cloud type and amount for global and regional climate change and vice versa, they did not speculate on the climatic implications of their findings, noting "it will be important to prepare cloud datasets for the more recent years [post 1996], when changes may become more noticeable with increased global warming."

The IPCC claims in AR5 that "the net radiative feedback due to all cloud types is likely positive" (p. 9 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). Contrary to that assessment, as shown in this section and the preceding section of this chapter, substantial research indicates the net global effect of cloud feedbacks is one of cooling, the magnitude of which may equal or exceed the warming projected from increasing greenhouse gases.

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2.5 Aerosols

Aerosols are an important factor in global temperature because they affect Earth's energy budget through their ability to reflect and scatter light and their propensity to absorb and radiate thermal radiation. In its *Fifth Assessment Report* (AR5), the IPCC concludes "the total aerosol effect is estimated as [a radiative forcing] of -0.7 and [an adjusted forcing] of -0.9 W m^{-2}" (p. 8-4 of Chapter 8, Second Order Draft of AR5, dated October 5, 2012). Such estimates were revised downward (a less-negative feedback) from the IPCC's *Fourth Assessment Report*, but as demonstrated in this section, many studies indicate aerosols are capable of producing a much stronger cooling effect, thus calling into question the IPCCs decision to downgrade the strength of this negative feedback. Several studies suggest the radiative forcing of aerosols may be as large as, or larger than, the radiative forcing due to atmospheric CO_2.

Our review of aerosol studies begins with an analysis of the total aerosol effect on climate, followed by a separate discussion of four important aerosol categories: (1) Biological (Aquatic), (2) Biological (Terrestrial), (3) Non-Biological (Anthropogenic), and (4) Non-Biological (Natural).

2.5.1 Total Aerosol Effect

Ghan *et al*. (2001) studied the positive radiative forcings of greenhouse gases and the negative radiative forcings of anthropogenic aerosols, reporting current best estimates of "the total global mean present-day anthropogenic forcing range from 3 W m^{-2} to -1 W m^{-2}," which represents everything from a modest warming to a slight cooling. After performing their own analysis, they reduced the range somewhat but found it still stretched from a small cooling influence to a modest impetus for warming. "Clearly," they conclude, "the great uncertainty in the radiative forcing must be reduced if the observed climate record is to be reconciled with model predictions and if estimates of future climate change are to be useful in formulating emission policies."

Vogelmann *et al*. (2003) point out "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR [infrared] flux between 7 and 25 W m^{-2} (Sokolik *et al*., 1998)." They note "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al*., 1996; Jacobson, 2001) despite their potentially large forcing." The researchers used high-resolution spectra to obtain the IR radiative forcing at Earth's surface for aerosols encountered in the outflow from northeastern Asia, based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer from the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. They determined "daytime surface IR forcings are often a few W m^{-2} and can reach almost 10 W m^{-2} for large aerosol loadings." These values, in their words, "are comparable to or larger than the 1 to 2 W m^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times" and "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

Similar findings were reported by Chou *et al*. (2002), who analyzed aerosol optical properties retrieved from the satellite-mounted Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and used them in conjunction with a radiative transfer model of the planet's atmosphere to calculate the climatic effects of aerosols over Earth's major oceans. In general, this effort revealed "aerosols reduce the annual-mean net downward solar flux by 5.4 W m^{-2} at the top of the atmosphere, and by 5.9 W m^{-2} at the surface." During the large Indonesian fires of September-December 1997, however, the radiative impetus for cooling at the top of the atmosphere was more than 10 W m^{-2}, while it was more than 25 W m^{-2} at the surface of the sea in the vicinity of Indonesia.

Wild (1999) used a comprehensive set of collocated surface and satellite observations to calculate the amount of solar radiation absorbed in the atmosphere over equatorial Africa and compared the results with the predictions of three general circulation models of the atmosphere. The climate models did not properly account for spatial and temporal variations in atmospheric aerosol concentrations, leading them to predict regional and seasonal values of solar radiation absorption in the atmosphere with underestimation biases of up to 30 W m^{-2}. By way of comparison, as noted by Vogelmann *et al*., the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times is 1 to 2 W m^{-2}.

Aerosol uncertainties and the problems they generate figure prominently in a study by Anderson *et al*. (2003), who note there are two different ways by which the aerosol forcing of climate may be computed. The first is forward calculation, based, in their words, on "knowledge of the pertinent aerosol physics and chemistry." The second approach is inverse calculation, based on "the total forcing required to match climate model simulations with observed temperature changes."

The first approach utilizes known physical and chemical laws and assumes nothing about the outcome of the calculation. The second approach, in considerable contrast, is based on matching residuals, where the aerosol forcing is computed from what is required to match the calculated change in temperature with the observed change over some period of time. Consequently, in the words of Anderson *et al*., "to the extent that climate models rely on the results of inverse calculations, the possibility of circular reasoning arises."

Which approach do climate models typically employ? "Unfortunately," Anderson *et al*. write, "virtually all climate model studies that have included anthropogenic aerosol forcing as a driver of climate change have used only aerosol forcing values that are consistent with the inverse approach." Anderson *et al*. report the negative forcing of anthropogenic aerosols derived by forward calculation is "considerably greater" than that derived by inverse calculation; if forward calculation is employed, the results "differ greatly" and "even the sign of the total forcing is in question." This implies "natural variability (that is, variability not forced by anthropogenic emissions) is much larger than climate models currently indicate," they write. Anderson *et al*. conclude, "inferences about the causes of surface warming over the industrial period and about climate sensitivity may therefore be in error."

Schwartz (2004) also addressed the subject of uncertainty as it applies to the role of aerosols in climate models. Noting the National Research Council (1979) concluded "climate sensitivity [to CO_2 doubling] is likely to be in the range 1.5–4.5°C" and "remarkably, despite some two decades of intervening work, neither the central value nor the uncertainty range has changed," Schwartz opines this continuing uncertainty "precludes meaningful model evaluation by comparison with observed global temperature change or empirical determination of climate sensitivity" and "raises questions regarding claims of having reproduced observed large-scale changes in surface temperature over the 20th century."

Schwartz thus contends climate model predictions of CO_2-induced global warming "are limited at present by uncertainty in radiative forcing of climate change over the industrial period, which is dominated by uncertainty in forcing by aerosols," and if this situation is not improved, "it is likely that in another 20 years it will still not be possible to specify the climate sensitivity with [an] uncertainty range appreciably narrower than it is at present." He adds, "the need for reducing the uncertainty from its present estimated value by at least a factor of 3 and perhaps a factor of 10 or more seems inescapable if the uncertainty in climate sensitivity is to be reduced to an extent where it becomes useful for formulating policy to deal with global change."

Lubin and Vogelmann (2006) employed five multisensor radiometric data sets from the North Slope of Alaska to study how enhanced concentrations of anthropogenic aerosols originating from industrial regions of lower latitudes alter the microphysical properties of Arctic clouds via a process known as the first indirect effect of aerosols. They determined this phenomenon operates in low optically thin single-layered Arctic clouds, producing an increase in the downwelling flux of longwave (thermal) radiation. Under frequently occurring cloud types, they found anthropogenic aerosols regularly advected into the Arctic lead to an average increase of 3.4 W m^{-2} in the downward-directed thermal radiation flux at Earth's surface. The two researchers state "the observed longwave enhancement has climatological significance."

The work of Charlson *et al*. (2005) supports that assessment. They report the longwave radiative forcing provided by all greenhouse gas increases since the beginning of the industrial era amounts to 2.4 W m^{-2}, citing the work of Anderson *et al*. (2003). Similarly, Palle *et al*. (2004) state "the latest IPCC report argues for a 2.4 W m^{-2} increase in CO_2 longwave forcing since 1850." Consequently, if the calculations of Lubin and Vogelmann are correct, the longwave radiative forcing of the anthropogenic aerosols that are advected into the Arctic may be larger than the combined forcing of all greenhouse gas increases since the beginning of the industrial era, suggesting recent increases in anthropogenic aerosol emissions could be the primary source of whatever Arctic warming may have occurred in recent years.

Jaenicke *et al*. (2007) reviewed the status of research being conducted on biological materials in the atmosphere, which they denominate primary biological atmospheric particles or PBAPs. Originally, these particles were restricted to culture-forming units, including pollen, bacteria, mold, and viruses, but they also include fragments of living and dead organisms and plant debris, human and animal epithelial cells, broken hair filaments, parts of insects, shed feather fractions, etc., which they lumped together under the category of "dead biological matter."

With respect to the meteorological and climatic relevance of these particles, Jaenicke *et al*. note many PBAPs, including "decaying vegetation, marine plankton and bacteria are excellent ice nuclei," and "one can easily imagine the [IR] influence on cloud cover, climate forcing and feedback and global precipitation distribution."

In describing their own measurements and those of others, which they said "have now been carried out at several geographical locations covering all seasons of the year and many characteristic environments," Jaenicke *et al*. report, "by number and volume, the PBAP fraction is ~20 percent of the total aerosol, and appears rather constant during the year." In addition, they write "the impression prevails that the biological material, whether produced directly or shed during the seasons, sits on surfaces, ready to be lifted again in resuspension."

In a brief summation of their findings, the German researchers state "the overall conclusion can only be that PBAPs are a major fraction of atmospheric aerosols, and are comparable to sea salt over the oceans and mineral particles over the continents." Consequently, they note, "the biosphere must be a major source for directly injected biological particles, and those particles should be taken into account in understanding and modeling atmospheric processes." They further note "the IPCC-Report of 2007 does not even mention these particles" and "this disregard of the biological particles requires a new attitude."

Ramanathan *et al*. (2007) point out light-absorbing and light-scattering aerosols "contribute to atmospheric solar heating and surface cooling," and "the sum of the two climate forcing terms—the net aerosol forcing effect—is thought to be negative and may have masked as much as half of the global warming attributed to the recent rapid rise in greenhouse gases." They caution there is "at least a fourfold uncertainty in the aerosol forcing effect."

Ramanathan *et al*. studied this phenomenon as it has never been studied before, using "three lightweight unmanned aerial vehicles that were vertically stacked between 0.5 and 3 km over the polluted Indian Ocean." The unmanned vehicles "deployed miniaturized instruments measuring aerosol concentrations, soot amount and solar fluxes" within the atmospheric brown clouds (ABCs) demonstrated to envelop "most of Asia and the adjacent oceans" during "the six-month-long tropical dry season," when "convective coupling between the surface and the troposphere is weak [and] aerosol solar heating can amplify the effect of greenhouse gases in warming the atmosphere while simultaneously cooling the surface." The seven scientists report finding "atmospheric brown clouds enhanced lower atmospheric solar heating by about 50 per cent" during the period of their study. Over the Indian Ocean and Asia during the long tropical dry season, they conclude, general circulation model simulations suggest "atmospheric brown clouds contribute as much as the recent increase in anthropogenic greenhouse gases to regional lower atmospheric warming trends."

Vautard *et al*. (2009) analyzed the frequency of occurrence of low horizontal visibility conditions over the past three decades at 342 meteorological stations scattered throughout Europe at 0300, 0900, 1500, and 2100 Universal Time, comparing their results with concomitant changes in near-surface air temperature and with spatial and temporal variations in sulfur dioxide emissions. "By enabling less energy to be received at the surface during daytime," they point out, "the low-visibility phenomenon inhibits surface heating, and therefore induces a lower local temperature." Since low-visibility conditions were presumed to have declined over the three-decade period due to the implementation of more effective air pollution control measures, the researchers anticipated a warming trend would be evident in the temperature data.

The three researchers document "a massive decline (about 50% in 30 years) of low-visibility occurrence throughout Europe," and they report this decline was "spatially and temporally correlated with trends in sulfur dioxide emissions, suggesting a significant contribution of air-quality improvements" to the improvement in visibility. By statistically linking local visibility changes with temperature variations, they found "the reduction in low-visibility conditions could have contributed on average to about 10–20% of Europe's recent daytime warming and to about 50% of eastern European warming."

The work of Vautard *et al*. (2009) strongly suggests the cleaning-up of European air pollution over the past three decades has been responsible for much of that region's recent warming, and it is likely that effect has been seen elsewhere around the globe as well. Their findings also provide support for an urban heat island effect other researchers suggest has inflated the global temperature record.

Mischenko *et al*. (2007) presented a plot of the global monthly average of the column aerosol optical thickness (AOT) of the atmosphere that stretches from August 1981 to June 2005, which they developed from "the longest uninterrupted record of global satellite estimates of the column AOT over the oceans, the Global Aerosol Climatology Project (GACP) record." This record was derived from "the International Satellite Cloud Climatology Project (ISCCP) DX radiance data set," which is "composed of calibrated and sampled Advanced Very High Resolution Radiometer radiances."

As shown in Figure 2.5.1.1, "the green line reveals a long-term decreasing tendency in the tropospheric AOT," such that "the resulting decrease in the tropospheric AOT during the 14-year period [1991–2005] comes out to be 0.03." This trend, they note, "is significant at the 99% confidence level." They explain "observations of downward solar radiation fluxes at Earth's surface have shown a recovery from the previous decline known as global 'dimming', with the 'brightening' beginning around 1990." Their AOT record harmonizes with these observations as well as with estimated trends in primary anthropogenic emissions of SO_2 and black carbon, which they said are known to "contribute substantially to the global AOT."

These facts raise serious questions about attributions of late-twentieth-century global warming to the increase in the atmosphere's CO_2 concentration. As noted by Stanhill (2007), changes in the flux of solar radiation received at the surface of Earth as a consequence of the global dimming and brightening phenomena far exceed the changes in longwave radiative forcing produced by historical changes in the air's CO_2 content. These observations would appear to relegate anthropogenic CO_2 emissions to a much less important role in terms of their ability to elicit significant changes in Earth's surface temperature.

The IPCC and others contend recent global brightening is merely allowing CO_2-induced warming to become more evident, which enables them to further contend the CO_2 greenhouse effect is actually much stronger than originally believed, having been masked for some time by the cooling power of the prior buildup of the great aerosol load of the atmosphere. Consequently, proponents of the theory of CO_2-induced global warming, such as *Science* magazine's Richard Kerr, are found writing news

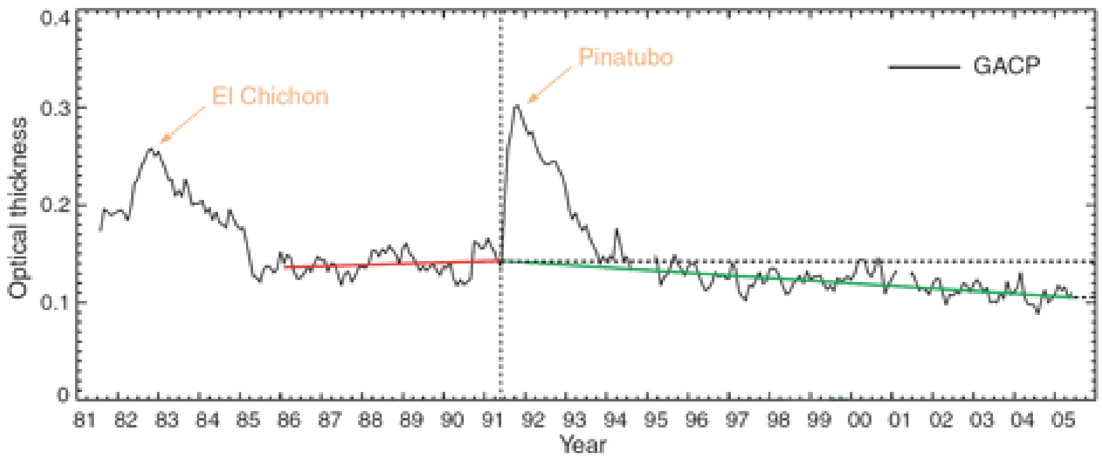

Figure 2.5.1.1. The GACP record of the globally averaged column AOT over the world's oceans. Adapted from Mishchenko, M.I., Geogdzhayev, I.V., Rossow, W.B., Cairns, B., Carlson, B.E., Lacis, A.A., Liu, L., and Travis, L.D. 2007. Long-term satellite record reveals likely recent aerosol trend. *Science* **315**: 1543.

items with titles that ask, "Is a thinning haze unveiling the real global warming?" (Kerr, 2007), when a better question to ask (or at least a reasonable alternative) might have been, "Is a thinning haze revealing its own great power to warm Earth?" Such writers seem to have no trouble finding scientists willing to cast doubt on what they perceive to be the disturbing implications of the unfolding aerosol work. In the case of Kerr's article, the doubter was Sarah Doherty of the University of Washington, who says there's simply too much uncertainty in the aerosol data and the problem lies, in part, "in stringing together records from five different instruments flown on five different satellites over the years."

As if anticipating such an attack, Mischenko *et al*. clearly state "the successful validation of GACP retrievals using precise Sun photometer data taken from 1983 through 2004 indicates that the ISCCP radiance calibration is likely to be reliable," and they further note "this conclusion is reinforced by the close correspondence of calculated and observed top of atmosphere solar fluxes." What is more, they state, "the GACP AOT record appears to be self-consistent, with no drastic intra-satellite variations, and is consistent with the Stratospheric Aerosol and Gas Experiment record."

Mischenko *et al*. present ample reason to suspect a significant portion of the observed warming of the twentieth century may have been caused not by increasing atmospheric CO_2 concentrations, but by the increase in surface heating provided by the atmosphere's declining aerosol optical thickness.

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2.5.2 Biological

In a Research Front article in *Environmental Chemistry*, Jaenicke *et al*. (2007) reviewed the status of research being conducted on biological materials in the atmosphere, which they denominated primary biological atmospheric particles or PBAPs. Originally, these particles were restricted to culture forming units, including pollen, bacteria, mold, and viruses, but they also include fragments of living and dead organisms and plant debris, human and animal epithelial cells, broken hair filaments, parts of insects, shed feather fractions, etc., which Jaenicke *et al*. (2007) categorized as dead biological matter.

With respect to the meteorological and climatic relevance of these particles, they note many PBAPs, including "decaying vegetation, marine plankton and bacteria are excellent ice nuclei"; "one can easily imagine [their] influence on cloud cover, climate forcing and feedback and global precipitation distribution," they write.

In describing their own measurements and those of others, which they said "have now been carried out at several geographical locations covering all seasons of the year and many characteristic environments," Jaenicke *et al*. report "by number and volume, the PBAP fraction is ~20% of the total aerosol, and appears rather constant during the year." The German researchers added, "the impression prevails that the biological material, whether produced directly or shed during the seasons, sits on surfaces, ready to be lifted again in resuspension." They conclude "PBAPs are a major fraction of atmospheric aerosols, and are comparable to sea salt over the oceans and mineral particles over the continents"; consequently, "the biosphere must be a major source for directly injected biological particles, and those particles should be taken into account in understanding and modeling atmospheric processes." They note "the IPCC-Report of 2007 does not even mention these particles" and "this disregard of the biological particles requires a new attitude."

As research summarized in the following two subsections demonstrates, biologically induced aerosols act as very real and significant feedbacks to global warming. The IPCC's "new attitude" must include a willingness to acknowledge that current climate models fail to capture many important forcings and feedbacks. When that which is missing is factored in and properly modeled, conclusions radically different from those currently offered by the IPCC are likely.

Others have come to this conclusion. The international team of scientists of Fuzzi *et al*. (2006)—researchers from Finland, Germany, Greece, Italy, Japan, Switzerland, and the United States—found "in spite of impressive advances in recent years ... our understanding of organic aerosol composition, physical and chemical properties, sources, transformation and removal characteristics is very limited, and estimates of their actual environmental effects are highly uncertain." They conclude, "a comprehensive characterization and mechanistic understanding of particle sources, properties, and transformation is required for quantitative assessment, reliable prediction, and efficient control of natural and anthropogenic aerosol effects on climate," and they identify a host of related "outstanding issues for future research."

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2.5.2.1 Aquatic

Perhaps the most researched aquatic aerosol feedback loop is the multistage negative feedback phenomenon involving dimethylsulfide, described many years ago by Charlson *et al*. (1987). In the ensuing years, much research has been conducted supporting various stages of this phenomenon, the topic of discussion in subsection 2.5.2.1.1 below.

But other biological aerosols of aquatic origin also have been shown by scientists to have the ability to significantly influence climate. The work of O'Dowd *et al*. (2002) describes one such feedback that by itself may have the capacity to thwart the CO_2 greenhouse effect.

Writing about the O'Dowd *et al*. research in a companion "news and views" article in *Nature*, Kolb (2002) noted the researchers had discovered "a previously unrecognized source of aerosol particles" by unraveling "a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides."

O'Dowd *et al*. used a smog chamber operated under coastal atmospheric conditions to demonstrate "new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae." With the help of aerosol formation models, they also demonstrated concentrations of condensable iodine-containing vapors over the open ocean "are sufficient to influence marine particle formation."

The aerosol particles O'Dowd *et al*. discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet. With respect to the negative feedback nature of this phenomenon, O'Dowd *et al*. cite the work of Laturnus *et al*. (2000), who demonstrated emissions of iodocarbons from marine biota "can increase by up to 5 times as a result of changes in environmental conditions associated with global change." As O'Dowd *et al*. note, "increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20–60%" and "changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global radiative forcing similar in magnitude, but opposite in sign, to the forcing induced by greenhouse gases."

Two years later and working with a different set of coauthors (O'Dowd *et al*., 2004), O'Dowd measured size-resolved physical and chemical properties of aerosols found in northeast Atlantic marine air arriving at the Mace Head Atmospheric Research station on the west coast of Ireland during phytoplanktonic blooms. In the winter, when biological activity was at its lowest, the research team found the organic fraction of the submicrometer aerosol mass was about 15 percent. In spring through autumn, when biological activity was high, they found "the organic fraction dominates and contributes 63% to the submicrometer aerosol mass (about 45% is water-insoluble and about 18% water-soluble)." O'Dowd *et al*. then performed model simulations indicating the marine-derived organic matter "can enhance the cloud droplet concentration by 15% to more than 100% and is therefore an important component of the aerosol-cloud-climate feedback system involving marine biota."

Such findings, the researchers state, "completely change the picture of what influences marine cloud condensation nuclei given that water-soluble organic carbon, water-insoluble organic carbon and surface-active properties, all of which influence the cloud condensation nuclei activation potential, are typically not parameterized in current climate models." They add, "an important source of organic matter from the ocean is omitted from current climate-modelling predictions and should be taken into account."

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2.5.2.1.1 Dimethylsulfide

According to the latest IPCC report, "there is *medium confidence* for a weak feedback involving dimethyl sulfide (DMS), cloud condensation nuclei (CCN), and cloud albedo due to a weak sensitivity of CCN population to changes in DMS emissions" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). A review of the scientific literature, however, reveals the strength of this negative feedback is likely much larger than the IPCC asserts, perhaps even strong enough to counter the threat of greenhouse gas-induced global warming.

Dimethylsulfide, or DMS, is an organosulfur compound with the formula $(CH_3)_2S$. It is the most abundant biologically produced sulfur compound in the atmosphere, emitted to the air primarily by marine phytoplankton.

Charlson *et al*. (1987) discussed the plausibility of a multistage negative feedback process whereby warming-induced increases in the emission of DMS from the world's oceans tend to counteract the effects of the initial impetus for warming. They hypothesized the global radiation balance is significantly influenced by the albedo of marine stratus clouds: the greater the cloud albedo, the less the input of solar radiation to Earth's surface. The albedo of these clouds, in turn, is known to be a function of cloud droplet concentration—the more and smaller the cloud droplets, the greater the cloud albedo and the reflection of solar radiation—which is dependent upon the availability of cloud condensation nuclei on which the droplets form: the more cloud condensation nuclei, the more and smaller the cloud droplets. In completing the negative feedback loop, Charlson *et al*. note the concentration of cloud condensation nuclei often depends upon the flux of biologically produced DMS from the world's oceans: the higher the sea surface temperature, the greater the sea-to-air flux of DMS.

Since the publication of Charlson *et al*.'s initial work, much empirical evidence has been gathered in support of their hypothesis. The review of Ayers and Gillett (2000), for example, concludes "major links in the feedback chain proposed by Charlson *et al*. (1987) have a sound physical basis" and there is "compelling observational evidence to suggest that DMS and its atmospheric products participate significantly in processes of climate regulation and reactive atmospheric chemistry in the remote marine boundary layer of the Southern Hemisphere."

Simo and Pedros-Alio (1999) used satellite imagery and *in situ* experiments to study the production of DMS by enzymatic cleavage of dimethylsulphoniopropionate in the North Atlantic Ocean about 400 km south of Iceland. They found the depth of the surface mixing-layer has a substantial influence on DMS yield in the short term, as do seasonal variations in vertical mixing in the longer term, which led them to conclude "climate-controlled mixing controls DMS production over vast regions of the ocean."

Hopke *et al*. (1999) analyzed weekly concentrations of 24 different airborne particulates measured at the northernmost manned site in the world—Alert, Northwest Territories, Canada—from 1980 to 1991. They found concentrations of biogenic sulfur, including sulfate and methane sulfonate, were low in winter but high in summer, and the year-to-year variability in the strength of the biogenic sulfur signal was strongly correlated with the mean temperature of the Northern Hemisphere. "This result," the authors state, "suggests that as the temperature rises, there is increased biogenic production of the reduced sulfur precursor compounds that are oxidized in the atmosphere to sulfate and methane sulfonate and could be evidence of a negative feedback mechanism in the global climate system."

Is that negative feedback phenomenon powerful enough to counter the threat of greenhouse gas-induced global warming? Sciare *et al*. (2000) examined ten years of DMS data from Amsterdam Island in the southern Indian Ocean, finding a sea surface temperature increase of only 1°C was sufficient to increase the atmospheric DMS concentration by as much as 50 percent. This finding suggests the degree of warming typically predicted to accompany a doubling of the air's CO_2 content would increase the atmosphere's DMS concentration by a factor of three or more, providing what they call a "very important" negative feedback that could potentially offset the original impetus for warming.

Kouvarakis and Mihalopoulos (2002) conducted research even more directly supportive of Charlson *et al*.'s hypothesis, measuring seasonal variations of gaseous DMS and its oxidation products—non-sea-salt sulfate (nss-$SO4^{2-}$) and methanesulfonic acid (MSA)—at a remote coastal location in the Eastern Mediterranean Sea from May 1997 through October 1999, as well as the diurnal variation of DMS during two intensive measurement campaigns conducted in September 1997. In the seasonal investigation, measured DMS concentrations tracked sea surface temperature (SST) almost perfectly, going from a low of 0.87 nmol m^{-3} in the winter to a high of 3.74 nmol m^{-3} in the summer. The diurnal studies reached a similar conclusion: DMS concentrations were lowest when it was coldest (just before sunrise), rose rapidly as it warmed thereafter to about 1,100, after which they dipped slightly and then experienced a further rise to the time of maximum temperature at 2,000, whereupon a decline in both temperature and DMS concentration set in that continued until just before sunrise. Because concentrations of DMS and its oxidation products rise dramatically in response to both diurnal and seasonal increases in SST, there is every reason to believe the same negative feedback phenomenon would operate in the case of the long-term warming that could arise from increasing greenhouse gas concentrations, substantially muting the climatic effects of those gases.

Baboukas *et al*. (2002) report the results of nine years of measurements of methanesulfonate (MS-), an exclusive oxidation product of DMS, in rainwater at Amsterdam Island. Their data, too, revealed "a well distinguished seasonal variation with higher values in summer, in line with the seasonal variation of its gaseous precursor (DMS)," which "further confirms the findings of Sciare *et al*. (2000)." The MS- anomalies in the rainwater were found to be closely related to SST anomalies; Baboukas *et al*. say this observation provides even more support for "the existence of a positive ocean-atmosphere feedback on the biogenic sulfur cycle above the Austral Ocean," which water body they describe as "one of the most important DMS sources of the world."

Toole and Siegel (2004) note the DMS negative feedback process has been shown to operate in the 15 percent of the world's oceans "consisting primarily of high latitude, continental shelf, and equatorial upwelling regions," where DMS may be accurately predicted as a function of the ratio of the amount of surface chlorophyll derived from satellite observations to the depth of the climatological mixed layer, which they refer to as the "bloom-forced regime." For the other 85 percent of the world's marine waters, they demonstrate modeled surface DMS concentrations are independent of chlorophyll and are a function of the mixed layer depth alone, which they called the "stress-forced regime." Their study revealed how the warming-induced DMS negative feedback cycle operates in these waters.

For oligotrophic regimes, Toole and Siegel found "DMS biological production rates are negatively or insignificantly correlated with phytoplankton and bacterial indices for abundance and productivity while more than 82% of the variability is explained by UVR(325) [ultraviolet radiation at 325 nm]." This relationship, in their words, is "consistent with recent laboratory results (e.g., Sunda *et al*., 2002)," which demonstrated intracellular DMS concentration and its biological precursors (particulate and dissolved dimethylsulfoniopropionate) "dramatically increase under conditions of acute oxidative stress such as exposure to high levels of UVR," which "are a function of mixed layer depth."

These results—which Toole and Siegel confirmed via an analysis of the Dacey *et al*. (1998) 1992–1994 organic sulfur time-series sampled in concert with the U.S. JGOFS Bermuda Atlantic Time-Series Study (Steinberg *et al*., 2001)—suggest, in their words, "the potential of a global change-DMS-climate feedback." Specifically, they state "UVR doses will increase as a result of observed decreases in stratospheric ozone and the shoaling of ocean mixed layers as a result of global warming (e.g., Boyd and Doney, 2002)," and "in response, open-ocean phytoplankton communities should increase their DMS production and ventilation to the atmosphere, increasing cloud condensing nuclei, and potentially playing out a coupled global change-DMS-climate feedback."

This second DMS-induced negative feedback cycle, which operates over 85 percent of the world's marine waters and complements the first DMS-induced negative feedback cycle, which operates over the other 15 percent, is another manifestation of the capacity of Earth's biosphere to regulate its affairs in such a way as to maintain climatic conditions over the vast majority of the planet's surface.

A DMS-induced negative climate feedback phenomenon may also operate over the terrestrial surface of the globe, where the volatilization of reduced sulfur gases from soils may be just as important as marine DMS emissions in enhancing cloud albedo (Idso, 1990). On the basis of experiments that showed soil DMS emissions to be positively correlated with soil organic matter content, for example, and noting additions of organic matter to a soil tend to increase the amount of sulfur gases emitted from it, Idso (1990) hypothesized that because atmospheric CO_2 is an effective aerial fertilizer, augmenting its atmospheric concentration and thereby increasing vegetative inputs of organic matter to Earth's soils should produce an impetus for cooling, even in the absence of surface warming.

About the same time Charlson *et al*. (1987) developed their hypothesis, Martin and Fitzwater (1988) and Martin *et al*. (1988) developed what has come to be known as the Iron Hypothesis (Martin, 1990), which posits that iron-rich dust swept up from exposed continental shelves during glacial maxima by the greatly enhanced winds of those periods fertilized the world's oceans to the point where their phytoplanktonic productivity rose so high it drew the air's CO_2 concentration down from typical interglacial values (280 ppm) to the much lower values characteristic of glacials (180 ppm). The IronEx studies of Martin *et al*. (1994) and Coale *et al*. (1996) confirmed the fundamental premise of this hypothesis. After fertilizing patches of seawater in high-nitrate low-chlorophyll (HNLC) regions of the equatorial Pacific with bio-available iron, they found, in the words of Turner *et al*. (2004), that this procedure "benefited all the major groups of the algal community, including those which produce significant amounts of intracellular dimethylsulfoniopropionate (DMSPp)," the precursor of DMS, which also increased in concentration as a result of the experimental iron treatment (Turner *et al*., 1996).

In the aftermath of these demonstrations, large-scale ocean fertilization with bio-available iron came to be viewed as a viable potential strategy for the mitigation of global warming. Not only could its implementation result in the quick removal of CO_2 from the atmosphere in response to heightened phytoplanktonic productivity, it could also lead to the reflection of more incoming solar radiation back to space as a result of greater DMSPp production.

But the studies supporting the second of these two pathways to planetary cooling had been conducted in the equatorial Pacific; it was not known whether the findings could be extrapolated to other HNLC ecosystems, such as those of the Southern Ocean. Thus, Turner *et al*. (2004) conducted two additional iron-release experiments: the Southern Ocean Iron Release Experiment (SOIREE), which took place south of Australia in February 1999, and EisenEx, which took place south of Africa in November 2000.

In both of these studies, Turner *et al*. reported "the experimental patches (~50 km²) were created by pumping dissolved iron sulfate into the mixed layer, as the ships sailed on a spiral track out from, and relative to, a buoy." The initial levels of dissolved iron in these patches rapidly decreased and additional injections were made during the experiments. "In SOIRRE," the scientists note, "the major increase in DMS occurred several days after the maximum in DMSPp and by the end of the study DMS levels at 30 m depth were 6.5-fold higher in treated waters than outside," while "in EisenEx, highest observed DMS concentrations [occurred] on days 5 and 12, about 2-fold higher than initial levels." They also report a series of ocean color images from SeaWiFS revealed a feature with enhanced chlorophyll levels close to the SOIREE site (Boyd *et al*., 2000), noting "Abraham *et al*. (2000) argue that this was our patch which had spread to cover 1100 km²."

Turner *et al*. report "recent coupled ocean-atmosphere modeling studies show that even a relatively small change in marine DMS emissions may have a significant impact on global temperatures: ± ~1°C for a halving or doubling of DMS emissions, respectively." In addition, they note "evidence from ice cores suggests that changes in DMS emission at least as large as this have occurred in the past (Legrand *et al*., 1991) and so it is easily conceivable that significant changes in DMS emissions would occur in future climate scenarios."

Operating in tandem, it is clear the marine-productivity-mediated increase in reflected solar radiation to space (via the Charlson *et al*. mechanism) and the more direct marine-productivity-mediated increase in the removal of CO_2 from the atmosphere possess the capacity to substantially counter whatever warming of the planet might occur in response to future anthropogenic CO_2 emissions.

In another study of the Charlson *et al*. (1987) hypothesis, Broadbent and Jones (2004) explored the possibility that coral reefs may be major participants in the biostabilization of Earth's climate. Working in waters off the coast of Australia, they note "Jones *et al*. (1994) and Broadbent *et al*. (2002) report that corals in the Great Barrier Reef (GBR) contain significant amounts of DMSP in their zooxanthellae, suggesting that coral reefs are potentially significant sources of DMS to the water column of reef areas and that coral reefs themselves may be significant sources of atmospheric DMS to the marine boundary layer (Jones and Trevena, 2005)." The two researchers measured concentrations of DMS and DMSP within mucus ropes, coral mucus, surface films, and sediment pore waters collected from Kelso Reef, One Tree Reef, and Nelly Bay Reef in Australia's GBR. Broadbent and Jones found "the concentrations of DMS and DMSP measured in mucus ropes and surface-water samples at One Tree Reef and Kelso Reef are the highest yet reported in the marine environment," exceeding those measured in "highly productive polar waters (Fogelqvist, 1991; Trevena *et al*., 2000, 2003), and sea ice algal communities (Kirst *et al*., 1991; Levasseur *et al*., 1994; Trevena *et al*., 2003)." They state, "concentrations of DMS ranged from 61 to 18,665 nM and for DMSP, from 1,978 to 54,381 nM, representing concentration factors (CF = concentration in the mucus ropes divided by the concentration in seawater from 0.5 m depth) ranging from 59 to 12,342 for DMS and 190 to 6,926 for DMSP." In addition, they report "concentrations of DMSP in coral mucus were also exceptionally high, with mucus from *Acropora formosa* containing the highest levels of DMSP." Finally, they observe DMS and DMSP concentrations were substantially higher than water-column concentrations in both surface microlayer samples and coral-reef sediment pore waters. Broadbent and Jones conclude "the elevated concentrations of DMS and DMSP in mucus ropes, coral mucus, surface films and sediment pore waters strongly suggest that coral reefs in the GBR are significant sources of these two sulphur substances," which in turn suggests coral reefs may figure prominently in the Charlson *et al*. phenomenon that helps to keep Earth's temperature from rising too high.

Jones and Trevena (2005) measured dissolved DMS, DMSP, the water-to-air flux of DMS, and atmospheric DMS concentration during a winter voyage through the northern GBR, Coral Sea, Gulf of Papua (GOP), and Solomon and Bismarck Seas. This work revealed the "highest levels of most of these constituents occurred in the northern GBR, NW Coral Sea and GOP, with highest levels of atmospheric DMS often occurring in south-easterly to southerly trade winds sampled in the region where the highest biomass of coral reefs occur." They also found the increase in atmospheric DMS "was mainly a result of a combination of high winds and the extremely low tides in July, when a high biomass of coral reefs in this region was aerially exposed." These findings helped solidify the link between coral zooxanthellae activity and the atmospheric concentration of DMS, which Broadbent and Jones (2004) called "a negative greenhouse gas"; i.e., one that tends to cool the planet. Thus, it broadens the base of the CLAW hypothesis (named for the four scientists of Charlson *et al*. (1987) who formulated it—**C**harlson, **L**ovelock, **A**ndreae, and **W**arren) and makes it more likely the hypothesis represents a viable mechanism for tempering, and possibly even capping, global warming.

Several additional studies have probed the robustness of the CLAW hypothesis. Gunson *et al*. (2006), for example, performed a number of climate simulations using a coupled ocean-atmosphere general circulation model that included an atmospheric sulfur cycle and a marine ecosystem model. They determined "the modeled global climate is sensitive to ocean DMS production in the manner hypothesized by CLAW" and "perturbations to ocean DMS production cause significant impacts on global climate." For a halving of oceanic DMS emissions, for example, they found the modeled net cloud radiative forcing increased by 3 W/m^2 and, through a readjustment of the global radiative energy balance, the surface air temperature rose by 1.6°C. For a doubling of oceanic DMS emissions, they found net cloud radiative forcing declined by just under 2 W/m^2 and the surface air temperature decreased by just under 1°C. These findings suggest Earth's climate system is indeed capable of successfully buffering itself against the propensity for warming created by rising atmospheric CO_2 concentrations.

Wong *et al*. (2006) recorded DMS concentrations and physical oceanographic data at ocean stations P20 and P26 in the Gulf of Alaska in the Northeast Pacific Ocean. As the sea surface temperature of a region rises, they found, "the stratification of the upper water column intensifies and oceanic upwelling weakens," such that "in the nutrient-rich waters of the sub-Arctic Pacific, higher stratification and shallower mixed layer favor the growth of small-sized phytoplankton such as flagellates, dinoflagellates and coccolithophorids." Noting "most prolific DMSP producers are members of these phytoplankton groups," they state, "consequently, the local ecosystem is shifted towards one with structure and function adapted to production of DMSP and DMS."

The four researchers point out, "globally, a larger part of the warming oceans may have highly stratified water for a longer part of the year," adding "these conditions could enhance the shift in the marine ecosystem described herein, and might induce more rapid turnover of DMSP and higher production of DMS," such that "in a warming global climate, we might anticipate an increasing emission of biogenic DMS from the ocean surface," which would tend to counteract whatever impetus for warming was causing sea surface temperatures to rise.

Also in 2006, Meskhidze and Nenes explored the effects of ocean biological productivity on the microphysical and radiative properties of marine clouds over a large and seasonally recurring phytoplankton bloom in the Southern Ocean in the vicinity of South Georgia Island, where upwelling nutrient-rich waters "can support massive phytoplankton blooms, with chlorophyll a concentrations more than an order of magnitude higher than the background." They used the Sea-viewing Wide Field-of-view Sensor to obtain the needed chlorophyll data and the Moderate Resolution Imaging Spectroradiometer to determine the effective radii of cloud condensation nuclei.

The researchers discovered "cloud droplet number concentration over the bloom was twice what it was away from the bloom, and cloud effective radius was reduced by 30%," such that "the resulting change in the short-wave radiative flux at the top of the atmosphere was -15 watts per square meter, comparable to the aerosol indirect effect over highly polluted regions." Meskhidze and Nenes conclude secondary organic aerosol formation in remote marine air may need to be included in global climate models, as it may play, as they describe it, "a considerable role in climate transition."

In another experiment, part of the Third Pelagic Ecosystem CO_2 Enrichment Study, Wingenter *et al*. (2007) investigated the effects of atmospheric CO_2 enrichment on marine microorganisms within nine marine mesocosms maintained within 2-m-diameter polyethylene bags submerged to a depth of 10 m in a fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espegrend, Norway. Three of these mesocosms were maintained at ambient levels of CO_2 (~375 ppm or base CO_2), three were maintained at levels expected to prevail at the end of the current century (760 ppm or $2xCO_2$), and three were maintained at levels predicted for the middle of the next century (1150 ppm or $3xCO_2$). During the 25 days of their experiment, the 12 researchers followed the development and subsequent decline of induced blooms of the coccolithophorid *Emiliania huxleyi* in the three CO_2 environments, carefully measuring several physical, chemical, and biological parameters along the way.

Wingenter *et al*.'s measurements and analyses indicated "dimethylsulfide production followed the development and decline of the phytoplankton bloom" and "maximum DMS concentrations coincided with the peak in chlorophyll-*a* concentrations in the present day CO_2 treatment, but were delayed by 1–3 days relative to chlorophyll-*a* in the double and triple CO_2 treatments." In addition, they found "DMS was 26% and 18% higher in the 2x and $3xCO_2$ mesocosms, respectively (days 0–17)." The iodocarbon chloroiodomethane (CH_2ClI) had its peak concentration about 6 to 10 days after the chlorophyll-*a* maximum, but its estimated abundance was 46 percent higher in the $2xCO_2$ mesocosms and 131 percent higher in the $3xCO_2$ mesocosms.

The international team of scientists concludes "the differences in DMS and CH_2ClI concentrations may be viewed as a result of changes to the ecosystems as a whole brought on by the CO_2 perturbations." Because emissions of both DMS (Bates *et al*., 1992) and various iodocarbons (O'Dowd *et al*., 2002; Jimenez *et al*., 2003) typically lead to an enhancement of cloud condensation nuclei in the marine atmosphere, the CO_2-induced stimulations of the marine emissions of these two substances provide a natural brake on the tendency for global warming to occur, as they lead to the creation of more highly reflective clouds over greater areas of the world's oceans. Consequently, as Wingenter *et al*. note, "these processes may help contribute to the homeostasis of the planet."

Vogt *et al*. (2008) also analyzed the effects of atmospheric CO_2 enrichment on marine microorganisms and DMS production under the same three CO_2 concentrations as those employed by Wingenter *et al*. (2007)—375, 760, and 1150 ppm—for a period of 24 days. They found no significant phytoplankton species shifts among treatments and noted "ecosystem composition, bacterial and phytoplankton abundances and productivity, grazing rates and total grazer abundance and reproduction were not significantly affected by CO_2-induced effects," citing in support of this statement the work of Riebesell *et al*. (2007), Riebesell *et al*. (2008), Egge *et al*. (2007), Paulino *et al*. (2007), Larsen *et al*. (2007), Suffrian *et al*. (2008), and Carotenuto *et al*. (2007). In addition, they note "while DMS stayed elevated in the treatments with elevated CO_2, we observed a steep decline in DMS concentration in the treatment with low CO_2" i.e., the ambient CO_2 treatment.

The eight researchers conclude "the system under study was surprisingly resilient to abrupt and large pH changes," contrary to what the IPCC characteristically predicts about CO_2-induced "ocean acidification." That may be why Vogt *et al*. describe the marine ecosystem they studied as "surprisingly" resilient.

Working in the coastal waters of Korea from November 21 to December 11, 2008, Kim *et al*. (2010) also conducted a CO_2 enrichment experiment, utilizing 2,400-liter mesocosm enclosures to simulate three sets of environmental conditions—an ambient control (~400 ppm CO_2 and ambient temperature), an acidification treatment (~900 ppm CO_2 and ambient temperature), and a greenhouse treatment (~900 ppm CO_2 and ~3°C warmer-than-ambient temperature). Within these mesocosms they initiated phytoplankton blooms by adding equal quantities of nutrients to each mesocosm on day 0, while for 20 days thereafter they measured numerous pertinent parameters within each mesocosm. They found "the total accumulated DMS concentrations (integrated over the experimental period) in the acidification and greenhouse mesocosms were approximately 80% and 60% higher than the values measured in the control mesocosms, respectively."

"Autotrophic nanoflagellates (which are known to be significant DMSP producers) showed increased growth in response to elevated CO_2," they note, and "grazing rates [of microzooplankton] were significantly higher in the treatment mesocosms than in the control mesocosms." Kim *et al*. conclude, "in the context of global environmental change, the key implication of our results is that DMS production resulting from CO_2-induced grazing activity may increase under future high CO_2 conditions" and, therefore, "DMS production in the ocean may act to counter the effects of global warming in the future."

Watanabe *et al*. (2007) utilized sea surface DMS data and other hydrographic parameters measured in the North Pacific Ocean between latitudes 25 and 55°N to develop and validate an empirical equation for sea surface DMS concentration that uses sea surface temperature, sea surface nitrate concentration, and latitude as input data. By applying the algorithm they developed to hydrographic time series data sets pertaining to the western North Pacific that span the period 1971 to 2000, the seven researchers found the annual flux of DMS from sea to air in that region increased by 1.9–4.8 µmol m^{-2} $year^{-1}$. This increase, they write, "was equal to the annual rate of increase of about 1% of the climatological annual averaged flux of DMS in the western North Pacific in the last three decades." These observations suggest the negative climate feedback phenomenon driven by increasing oceanic DMS concentrations is "alive and well."

Working with climate and DMS production data from the region of the Barents Sea (70-80°N, 30-35°E) obtained over the period 1998 to 2002, Qu and Gabric (2010) employed a genetic algorithm to calibrate chlorophyll-*a* measurements (obtained from SeaWiFS satellite data) for use in a regional DMS production model. Then, using GCM temperature outputs for the periods of 1960–1970 (pre-industry CO_2 level) and 2078–2086 (triple the pre-industry CO_2 level), they calculated the warming-induced enhancement of the DMS flux from the Barents Sea region. The two researchers report "significantly decreasing ice coverage, increasing sea surface temperature and decreasing mixed-layer depth could lead to annual DMS flux increases of more than 100% by the time of equivalent CO_2 tripling (the year 2080)." They state "such a large change would have a great impact on the Arctic energy budget and may offset the effects of anthropogenic warming that are amplified at polar latitudes" and add "many of these physical changes will also promote similar perturbations for other biogenic species (Leck *et al*., 2004), some of which are now thought to be equally influential to the aerosol climate of the Arctic Ocean."

One year later, working with *Phaeocystis antarctica*—a polar prymnesiophyte or haptophyte (marine microalga or phytoplankton)—Orellana *et al*. (2011) measured the concentrations of DMS and DMSP in whole cells and isolated secretory vesicles of the species as well as in samples of broken cells, because, as they elucidated, "in addition to autolysis (Hill *et al*., 1998), viral lysis (Malin *et al*., 1998), and zooplankton grazing (Dacey and Wakeham, 1986;

Wolfe and Steinke, 1996), it is believed that DMSP passively diffuses into seawater." They note "understanding the regulation of this mechanism is necessary in order to obtain a correct partitioning of the cellular and extracellular DMSP and DMS pools in seawater and allow predictions of global budgets." The four U.S. researchers demonstrate "DMSP and DMS were stored in the secretory vesicles of *Phaeocystis antarctica*," where "they were trapped within a polyanionic gel matrix, which prevented an accurate measurement of their concentration in the absence of a chelating agent." They conclude, "the pool of total DMSP in the presence of *Phaeocystis* may be underestimated by as much as half."

Noting "models for the distribution of marine DMS have lately been increasing in number and complexity, such that a regional portrait of their evolving climate response is constructible," Cameron-Smith *et al*. (2011) employed the most recent version of the Community Climate System Model (CCSM), described by Collins *et al*. (2006), to produce the first marine sulfur simulations performed with what they refer to as "the most sophisticated ocean sulfur cycle model yet reported."

In one of their simulations, the atmospheric CO_2 concentration was held steady at 355 ppm, while in another it was set at 970 ppm in order to simulate the climate near the end of the twenty-first century as projected by the IPCC (2001) SRES A1F1 emissions scenario. The latter CO_2 concentration and its modeled climatic consequences resulted in the simulation of "rings of high DMS near Antarctica due to the inclusion of a *Phaeocystis* parameterization." This unicellular, photosynthetic, eukaryotic alga generates, in the words of the five U.S. scientists, "several times the typical DMSP level (dimethyl sulfoniopropionate, a major DMS precursor) and favors cold water habitat (Matrai and Vernet, 1997)."

Consequently, the modeled global warming produced by the specified increase in the atmosphere's CO_2 concentration resulted in a migration of *Phaeocystis* species toward the cooler waters of higher latitudes. Under these conditions the model employed by Cameron-Smith *et al*. simulated increases in the "zonal averaged DMS flux to the atmosphere of over 150% in the Southern Ocean," which they report was "due to concurrent sea ice changes and ocean ecosystem composition shifts caused by changes in temperature, mixing, nutrient, and light regimes." Based on other modeling exercises they conducted, they state the shift in the location of maximum DMS emissions towards colder regions "is usually reinforced with even more sophisticated models."

Cameron-Smith and colleagues conclude, "in global estimates involving constant upward or downward DMS flux changes, average planetary surface temperatures separate by three or more degrees Celsius," citing the work of Charlson *et al*. (1987) and Gunson *et al*. (2006). This strong biological response to a CO_2-induced impetus for warming can result in a greatly strengthened negative regional feedback that results in more incoming solar radiation being reflected back to space with enhanced regional cooling. The resulting DMS-enhanced "thermal insulating" of Antarctica from the rest of the world by this mechanism could significantly reduce the propensity for that continent's ice sheets to lose mass and contribute to sea level rise, even in a world that is experiencing a net warming.

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2.5.2.2 Terrestrial

Just as marine phytoplankton respond to rising temperatures by emitting gases that ultimately lead to less global warming, so too do terrestrial plants. What is more, Earth's terrestrial plants have a tendency to operate in this manner more effectively as the air's CO_2 content rises.

A good introduction to this subject is provided by the review paper of Peñuelas and Llusia (2003), who point out biogenic volatile organic compounds (BVOCs) constitute "one of nature's biodiversity treasures." Comprised of isoprene, terpenes, alkanes, alkenes, alcohols, esters, carbonyls, and acids, this diverse group of substances is produced by a variety of processes occurring in many plant tissues. Some of the functions of these substances, according to the two scientists, include acting as "deterrents against pathogens and herbivores, or to aid wound sealing after damage (Pichersky and Gershenzon, 2002)." They also state BVOCs provide a means "to attract pollinators and herbivore predators, and to communicate with other plants and organisms (Peñuelas *et al*., 1995; Shulaev *et al*., 1997)."

Of particular importance within the context of global climate change, in the opinion of Peñuelas and Llusia, is the growing realization that "isoprene and monoterpenes, which constitute a major fraction of BVOCs, might confer protection against high temperatures" by acting "as scavengers of reactive oxygen species produced [within plants] under high temperatures." The claimed ill effects of CO_2-induced global warming on Earth's vegetation thus may be countered by two ameliorative phenomena: the aerial fertilization effect of atmospheric CO_2 enrichment, which is typically more strongly expressed at higher temperatures, and the tendency for rising air temperatures and CO_2 concentrations to spur the production of higher concentrations of heat-stress-reducing BVOCs. With respect to temperature, Peñuelas and Llusia calculate "global warming over the past 30 years could have increased the BVOC global emissions by approximately 10 percent, and a further 2–3°C rise in the mean global temperature ... could increase BVOC global emissions by an additional 30-45 percent."

Other phenomena may similarly favor plants. Peñuelas and Llusia note "the increased release of nitrogen into the biosphere by man probably also enhances BVOC emissions by increasing the level of carbon fixation and the activity of the responsible enzymes (Litvak *et al*., 1996)." The conversion of abandoned agricultural lands to forests and the implementation of planned reforestation projects should help the rest of the biosphere too; Peñuelas and Llusia report additional numbers of "*Populus*, *Eucalyptus* or *Pinus*, which are major emitters, might greatly increase BVOC emissions."

With respect to how increased BVOC emissions might affect climate change itself, Peñuelas and Llusia point out "BVOCs generate large quantities of organic aerosols that could affect climate significantly by forming cloud condensation nuclei." They conclude, "there should be a net cooling of the Earth's surface during the day because of radiation interception," noting Shallcross and Monks (2000) "have suggested that one of the reasons plants emit the aerosol isoprene might be to cool the surroundings in addition to any physiological or evaporative effects that might cool the plant directly."

Not all experiments have reported increases in plant BVOC emissions with increasing atmospheric CO_2 concentrations. Rapparini *et al*. (2004) found long-term exposure to high levels of atmospheric CO_2 did not significantly affect BVOC emissions from mature downy and holly oak trees growing close to a natural CO_2 spring in central Italy. Similarly, Constable *et al*. (1999) reported no effect of elevated CO_2 on monoterpene emissions from Ponderosa pine and Douglas fir trees. And some studies have reported decreases in BVOC emissions, such as those of Vuorinen *et al*. (2004), who worked with cabbage plants, and Loreto *et al*. (2001), who studied monoterpene emissions from oak seedlings. But Staudt *et al*. (2001) observed CO_2-induced increases in BVOC emissions in the identical species of oak studied by Vuorinen *et al*. (2004).

An explanation for this wide range of results comes from Baraldi *et al*. (2004), who—after exposing sections of a southern California chaparral ecosystem to atmospheric CO_2 concentrations ranging from 250 to 750 ppm in 100-ppm increments for a period of four years—concluded "BVOC emission can remain nearly constant as rising CO_2 reduces emission per unit leaf area while stimulating biomass growth and leaf area per unit ground area." In most of the cases investigated, however, BVOC emissions tended to increase with atmospheric CO_2 enrichment, and the increases were often large.

Jasoni *et al*. (2003), for example, grew onions from seed for 30 days in individual cylindrical flow-through growth chambers under controlled environmental conditions at atmospheric CO_2 concentrations of either 400 or 1,000 ppm. At the end of the study, the plants in the CO_2-enriched chambers had 40 percent more biomass than the plants grown in ambient air, and their photosynthetic rates were 22 percent greater. In addition, the CO_2-enriched plants exhibited 17-fold and 38-fold increases in emissions of the BVOC hydrocarbons 2-undecanone and 2-tridecanone, respectively, which Jasoni *et al*. note "confer insect resistance against a major agricultural pest, spider mites." They conclude "plants grown under elevated CO_2 will accumulate excess carbon and at least a portion of this excess carbon is funneled into an increased production of BVOCs."

Focusing on actively wet-spore-discharging Ascomycota (AAM) and actively wet-spore-discharging Basidiomycota (ABM), Elbert *et al*. (2007) "address the active (forcible) discharge of fungal spores, which is accompanied by the emission of aqueous droplets containing carbohydrates and inorganic ions, ... summarize the information on the atmospheric abundance of wet and dry discharged fungal spores that is available from earlier scientific studies made at various locations around the world, ... and present new measurement results and budget calculations for aerosol samples from tropical rainforests in Amazonia." The four researchers confirmed AAM and ABM are major sources of primary biogenic aerosols, finding from their own work that "in pristine tropical rainforest air, fungal spores indeed account for a major fraction of coarse particulate matter (up to ~45%)." They also calculated the emission rate of total fungal spores (~50 Tg yr^{-1}) "is of similar magnitude as current estimates of the rates of emission and formation of other types of continental air particulate matter (primary and secondary organic aerosols)."

Of particular interest in the context of rising near-surface air temperatures and atmospheric CO_2 concentrations, Elbert *et al*. write, "global warming and increasing CO_2 concentrations may enhance the spread of fungi and emission of fungal spores," citing the works of Klironomos *et al*. (1997), Hoye *et al*. (2007), and Raupach *et al*. (2007), while further concluding "an increase of fungal spores acting as cloud condensation and ice nuclei may influence the hydrological cycle and provide either positive or negative feedbacks to climate change."

Raisanen *et al*. (2008) sought to determine to what extent a doubling of the air's CO_2 content and a 2°–6°C increase in air temperature might affect the emission of monoterpenes from 20-year-old Scots pine (*Pinus sylvestris* L.) seedlings. They studied the two phenomena and their interaction within closed-top chambers built on a naturally seeded stand of the trees in eastern Finland that had been exposed to the four treatments—ambient CO_2 and ambient temperature, ambient temperature and elevated CO_2, ambient CO_2 and elevated temperature, elevated temperature and elevated CO_2—for the prior five years.

Over the five-month growing season of May-September, the three Finnish researchers found total monoterpene emissions in the elevated-CO_2-only treatment were 5 percent greater than those in the ambient CO_2, ambient temperature treatment. Emissions in the elevated-temperature-only treatment were 9 percent less than those in ambient air. In the presence of both elevated CO_2 and elevated temperature, there was an increase of fully 126 percent in the total amount of monoterpenes emitted over the growing season, which led the authors to conclude, "the amount of monoterpenes released by Scots pines into the atmosphere during a growing season will increase substantially in the predicted future climate."

Kavouras *et al*. (1998) measured a number of atmospheric gases and particles in a eucalyptus forest in Portugal and analyzed their observations for evidence of biologically produced gases being converted to particles that could function as cloud condensation nuclei. They found certain hydrocarbons emitted by vegetation (isoprene and terpenes, in particular) do indeed experience gas-to-particle transformations. Aerosols (or *bio*sols) produced from two of these organic acids (cis- and trans-pinonic acid) comprised as much as 40 percent of the fine particle atmospheric mass during daytime hours.

A similar study was conducted by O'Dowd *et al*. (2002), who measured aerosol electrical-mobility size-distributions before and during the initial stage of an atmospheric nucleation event over a boreal forest in Finland. Simultaneously, organic vapor growth rate measurements were made of particles that nucleated into organic cloud-droplets in the flow-tube cloud chamber of a modified condensation-particle counter. They determined newly formed aerosol particles over forested areas "are composed primarily of organic species, such as cis-pinonic acid and pinonic acid, produced by oxidation of terpenes in organic vapors released from the canopy." They point out "aerosol particles produced over forested areas may affect climate by acting as nuclei for cloud condensation," adding there remain numerous uncertainties involving complex feedback processes "that must be determined if we are to predict future changes in global climate."

Also working in Finland, Tunved *et al*. (2006) analyzed a five-year (1999–2004) April–September database of aerosol number-size distribution obtained from three monitoring stations in the Finnish boreal zone of Europe—Varrio (67°46'N, 29°35'E), Pallas (68°01'N, 24°10'E), and Hyytiala (61°51'N, 24°17'E)—in an investigation of "the characteristic changes of the aerosol population in air masses undergoing marine to continental transition over forested areas in northern Norway, Sweden and Finland" that are "substantially lacking in anthropogenic aerosol sources." According to the ten European researchers authoring this study, their results "clearly show that a substantial gas-to-particle [trans]formation of biogenic volatile organic carbon [BVOC] to secondary organic aerosol [SOA] takes place over the boreal forest in northern Europe" and "these BVOCs are most likely emitted from the forest itself and, based on previous findings, are most likely constituted of terpenes."

Their analysis further "suggests an apparent mass yield in the range of 5 to 10%" and that "the boreal forest typically sustains 1000 to 2000 particles cm^{-3} in a climatic relevant size range (~40 to 100 nm)." Because they "provided a similar mechanistic and quantitative behavior for two widely separate locations (more than 700 km apart)," they report, "the derived relations suggest that similar mechanisms control the aerosol number and mass evolution over large areas in the boreal regions of the Northern Hemisphere." Tunved *et al*. conclude their findings have "important implications for radiation budget estimates and relevancy for the evaluation of feedback loops believed to determine our future climate," noting their study establishes that boreal forest "is a major source of climate-relevant aerosol particles" "capable of competing with the anthropogenic CCN [cloud condensation nuclei] loadings transported over forested areas."

Shifting from trees to a much smaller plant, Kuhn and Kesselmeier (2000) collected lichens from an open oak woodland in central California, USA and studied their uptake of carbonyl sulfide (COS) in a dynamic cuvette system under controlled conditions in the laboratory. When the lichens were optimally hydrated, COS was absorbed from the atmosphere by the lichens at a rate that gradually doubled as air temperature rose from approximately 3° to 25°C, whereupon the rate of COS absorption dropped precipitously, reaching a value of zero at 35°C.

COS is the most stable and abundant reduced sulfur gas in the atmosphere and a major player in determining Earth's radiation budget. After making its way into the stratosphere, it can be photo-dissociated, as well as oxidized, to form SO_2, which is typically converted to sulfate aerosol particles that are highly reflective of incoming solar radiation and, therefore, have the capacity to significantly cool Earth as more and more of them collect above the tropopause. Biologically modulated COS concentrations may play a role in regulating Earth's surface air temperature.

Once air temperature rises above 25°C, the rate of removal of COS from the air by this species of lichen declines dramatically. More COS thus remains in the air and is likely to make its way into the stratosphere, where it can be converted into sulfate aerosol particles that can reflect more incoming solar radiation back to space and thereby cool Earth. Since the consumption of COS by lichens is under the physiological control of carbonic anhydrase, which is the key enzyme for COS uptake in all higher plants, algae, and soil organisms, this phenomenon is likely to be generally operative throughout much of the plant kingdom. This biological "thermostat" may be powerful enough to define an upper limit above which the surface air temperature of the planet may be restricted from rising, even when changes in other forcing factors, such as greenhouse gases, produce an impetus for it to do so. (For more about COS, see Section 2.6.2 below.)

Although BVOCs emitted from terrestrial plants both small and large are important to Earth's climate, trees tend to dominate. Recent research suggests another way in which their response to atmospheric CO_2 enrichment may provide an effective counterbalance to the greenhouse properties of CO_2.

The phenomenon begins with the propensity for CO_2-induced increases in BVOCs, together with the cloud particles they spawn, to enhance the amount of diffuse solar radiation reaching Earth's surface

(Suraqui *et al*., 1974; Abakumova *et al*., 1996). That is followed by the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies (Roderick *et al*., 2001), followed by the tendency for less internal canopy shading to enhance whole-canopy photosynthesis (Healey *et al*., 1998). The end result is a greater photosynthetic extraction of CO_2 from the air and subsequent reduction of the strength of the atmosphere's greenhouse effect.

The significance of this process is described and documented at some length in Section 2.6.3 of this report. For example, Roderick *et al*. conclude the Mt. Pinatubo eruption—a unique natural experiment to evaluate the overall climatic sensitivity of the planet—may have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial photosynthesis in the year following the eruption. Additional real-world evidence for the existence of this phenomenon was provided by Gu *et al*. (2003), Law *et al*. (2002), Farquhar and Roderick (2003), Reichenau and Esser (2003), and Niyogi *et al*. (2004).

One final beneficial effect of CO_2-induced increases in BVOC emissions is the propensity of BVOCs to destroy tropospheric ozone, as documented by Goldstein *et al*. (2004). Earth's vegetation is responsible for the production of vast amounts of ozone (O_3) (Chameides *et al*., 1988; Harley *et al*., 1999), but it is also responsible for destroying much of it. Goldstein *et al*. mention three major routes by which O_3 exits the air near Earth's surface: leaf stomatal uptake, surface deposition, and within-canopy gas-phase chemical reactions with BVOCs.

The first of these exit routes, according to Goldstein *et al.,* accounts for 30 to 90 percent of total ecosystem O_3 uptake from the atmosphere (that is, O_3 destruction), and the remainder typically has been attributed to deposition on non-stomatal surfaces. However, they note "Kurpius and Goldstein (2003) recently showed that the non-stomatal flux increased exponentially as a function of temperature at a coniferous forest site," and "the exponential increase with temperature was consistent with the temperature dependence of monoterpene emissions from the same ecosystem, suggesting O_3 was lost via gas phase reactions with biogenically emitted terpenes before they could escape the forest canopy."

Schade and Goldstein (2003) had demonstrated forest thinning dramatically enhances monoterpene emissions. Goldstein *et al*. (2004) took another important step toward clarifying the issue by measuring the effect of forest thinning on O_3 destruction in an attempt to see if it is enhanced along with the thinning-induced increase in monoterpene emissions.

In a ponderosa pine plantation in the Sierra Nevada Mountains of California, USA, a management procedure to improve forest health and optimize tree growth was initiated on May 11, 2000 and continued through June 15, 2000. This procedure involved the use of a masticator to mechanically "chew up" smaller unwanted trees and leave their debris on site, which reduced plantation green leaf biomass by just over half. Monoterpene mixing ratios and fluxes were measured hourly within the plantation canopy, while total ecosystem O_3 destruction was "partitioned to differentiate loss due to gas-phase chemistry from stomatal uptake and deposition."

Goldstein *et al*. report both the destruction of ozone due to gas-phase chemistry and emissions of monoterpenes increased dramatically with the onset of thinning, and these phenomena continued in phase with each other thereafter. They "infer that the massive increase of O_3 flux during and following mastication is driven by loss of O_3 through chemical reactions with unmeasured terpenes or closely related BVOCs whose emissions were enhanced due to wounding [by the masticator]." The write, "considered together, these observations provide a conclusive picture that the chemical loss of O_3 is due to reactions with BVOCs emitted in a similar manner as terpenes" and "we can conceive no other possible explanation for this behavior other than chemical O_3 destruction in and above the forest canopy by reactions with BVOCs."

Goldstein *et al*. conclude their results "suggest that total reactive terpene emissions might be roughly a factor of 10 higher than the typically measured and modeled monoterpene emissions, making them larger than isoprene emissions on a global scale." This would mean vegetative emissions of terpenes, which lead to the destruction of ozone, are significantly greater than vegetative emissions of isoprene, which lead to the creation of ozone (Poisson *et al*., 2000). In addition, there is substantial evidence to suggest the ongoing rise in the air's CO_2 content may lead to an overall reduction in vegetative isoprene emissions while enhancing vegetative productivity, which may lead to an overall increase in vegetative terpene emissions. There is thus reason to believe the ongoing rise in the air's CO_2 content will help reduce the ongoing rise in the air's O_3 concentration.

There is growing evidence that rising air temperatures and atmospheric CO_2 concentrations significantly increase desirable vegetative BVOC emissions, particularly from trees—the most prominent photosynthetic force on the planet—and that this phenomenon has important and highly beneficial biospheric consequences. These findings further demonstrate that the biology of Earth influences the climate of Earth. They reveal a direct connection between the metabolic activity of trees and the propensity for the atmosphere to produce clouds; the metabolic activity of lichens and the presence of sulfate aerosol particles in the atmosphere that reflect incoming solar radiation; and the increased presence of BVOCs caused by rising CO_2 and an increase in diffuse solar radiation, which leads to increased photosynthetic extraction of CO_2 from the air. In each case, the relationship is self-protecting of the biosphere, and in each case the feedbacks are either ignored or downplayed by the IPCC.

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2.5.2.2.1 Isoprene

Isoprene (C_5H_8 or 2-methyl-1,3-butadiene) is a highly reactive non-methane hydrocarbon (NMHC) emitted by vegetation; it is responsible for the production of tropospheric ozone (Chameides *et al*., 1988; Harley *et al*., 1999), a debilitating scourge of plant and animal life alike. Poisson *et al*. (2000) calculated current levels of NMHC emissions—the vast majority of which are isoprene, accounting for more than twice as much as all other NMHCs combined—may increase surface ozone concentrations by up to 40 percent in the marine boundary-layer and 50 to 60 percent over land. They further estimated the current tropospheric ozone content extends the atmospheric lifetime of methane, one of the world's most powerful greenhouse gases, by approximately 14 percent.

A few experiments have suggested elevated concentrations of atmospheric carbon dioxide have little or no effect on the emission of isoprene by certain plant species (Buckley, 2001; Baraldi *et al*., 2004; Rapparini *et al*., 2004). But a much larger number of experiments suggest substantial CO_2-induced reductions in isoprene emissions, as demonstrated by the work of Monson and Fall (1989), Loreto and Sharkey (1990), Sharkey *et al*. (1991), and Loreto *et al*. (2001). We here provide short synopses of several other such studies along with some of the implications of their more robust findings.

Rosentiel *et al*. (2003) studied three 50-tree cottonwood plantations growing in separate mesocosms within the forestry section of the Biosphere 2 facility near Oracle, Arizona, USA. One of these mesocosms was maintained at an atmospheric CO_2 concentration of 430 ppm, while the other two were enriched to concentrations of 800 and 1,200 ppm for an entire growing season. Integrated over that period, the total above-ground biomass of the trees in the latter two mesocosms was increased by 60 percent and 82 percent, respectively, while their production of isoprene was decreased by 21 percent and 41 percent, respectively.

Scholefield *et al*. (2004) measured isoprene emissions from *Phragmites australis* (a grass) growing at different distances from a natural CO_2 spring in central Italy. Atmospheric CO_2 concentrations of approximately 350, 400, 550, and 800 ppm had likely prevailed at the locations they measured for the entire lifetimes of the plants. Across this CO_2 gradient, plant isoprene emissions fell as the air's CO_2 concentration rose. Over the first 50 ppm CO_2 increase, isoprene emissions were reduced to approximately 65 percent of what they were at ambient CO_2; for CO_2 increases of 200 and 450 ppm, isoprene emissions were reduced to about 30 percent and 7 percent of what they were in the 350-ppm-CO_2 air. The researchers note these reductions were likely caused by reductions in leaf isoprene synthase, which was observed to be highly correlated with isoprene emissions. This led them to conclude, "elevated CO_2 generally inhibits the expression of isoprenoid synthesis genes and isoprene synthase activity which may, in turn, limit formation of every chloroplast-derived isoprenoid." They thus state the "basal emission rate of isoprene is likely to be reduced under future elevated CO_2 levels."

Centritto *et al*. (2004) grew hybrid poplar saplings for one full growing season in a forced-air CO_2 enrichment (FACE) facility located at Rapolano, Italy, where the air's CO_2 concentration was increased by approximately 200 ppm. They found "isoprene emission is reduced in elevated CO_2, in terms of both maximum values of isoprene emission rate and isoprene emission per unit of leaf area averaged across the total number of leaves per plant," a reduction of approximately 34 percent. When isoprene emission was summed over the entire plant profile, the reduction was not nearly so great (only 6 percent), because of the greater number of leaves on the CO_2-enriched saplings. "However," they point out, "Centritto *et al*. (1999), in a study with potted cherry seedlings grown in open-top chambers, and Gielen *et al*. (2001), in a study with poplar saplings exposed to FACE, showed that the stimulation of total leaf area in response to elevated CO_2 was a transient effect, because it occurred only during the first year of growth." Thus, they conclude, "it may be expected that with similar levels of leaf area, the integrated emission of isoprene would have been much lower in elevated CO_2." They say their work, "as well as that reported by Scholefield *et al*. (2004), in a companion experiment on *Phragmites* growing in a nearby CO_2 spring, mostly confirm that isoprene emission is inversely dependent on CO_2 [concentration] when this is above ambient, and suggests that a lower fraction of C will be re-emitted in the atmosphere as isoprene by single leaves in the future."

Working at the Aspen FACE facility near Rhinelander, Wisconsin, USA, Calfapietra *et al*. (2008) measured emissions of isoprene from sun-exposed upper-canopy leaves of an O_3-tolerant clone and an O_3-sensitive clone of trembling aspen (*Populus tremuloides* Michx.) trees growing in either normal ambient air, air enriched with an extra 190–200 ppm CO_2, air with 1.5 times the normal ozone concentration, or air simultaneously enriched with the identical concentrations of both gases.

For trees growing in air of ambient ozone concentration, the extra 190 ppm of CO_2 decreased the mean isoprene emission rate by 11.7 percent in the O_3-tolerant aspen clone and by 22.7 percent in the O_3-sensitive clone. For trees growing in air with 1.5 times the ambient ozone concentration, the extra CO_2 decreased the mean isoprene emission rate by 10.4 percent in the O_3-tolerant clone and by 32.7 percent in the O_3-sensitive clone. At the same time, and in the same order, net photosynthesis rates were increased by 34.9 percent, 47.4 percent, 31.6 percent, and 18.9 percent.

Possell *et al*. (2004) grew seedlings of English oak (*Quercus robur*), one to a mesocosm (16 cm diameter, 60 cm deep), in either fertilized or unfertilized soil in solardomes maintained at atmospheric CO_2 concentrations of either ambient or ambient plus 300 ppm for one full year, at the conclusion of which period they measured rates of isoprene emissions from the trees' foliage together with their rates of photosynthesis. In the unfertilized trees, the 300 ppm increase in the air's CO_2 concentration reduced isoprene emissions by 63 percent on a leaf area basis and 64 percent on a biomass basis, while in the fertilized trees the extra CO_2 reduced isoprene emissions by 70 percent on a leaf area basis and 74 percent on a biomass basis. In addition, the extra CO_2 boosted leaf photosynthesis rates by 17 percent in the unfertilized trees and 13 percent in the fertilized trees.

Possell *et al*. (2005) performed multiple three-week-long experiments with two known isoprene-emitting herbaceous species (*Mucuna pruriens* and *Arundo donax*), which they grew in controlled environment chambers maintained at two different sets of day/night temperatures (29/24°C and 24/18°C) and atmospheric CO_2 concentrations characteristic of glacial (180 ppm), preindustrial (280 ppm), and current (366 ppm) conditions, where canopy isoprene emission rates were measured on the final day of each experiment. They obtained what they describe as "the first empirical evidence for the enhancement of isoprene production, on a unit leaf area basis, by plants that grew and developed in [a] CO_2-depleted atmosphere." These results, in their words, "support earlier findings from short-term studies with woody species (Monson and Fall, 1989; Loreto and Sharkey, 1990)."

Then, combining their emission rate data with those of Rosenstiel *et al*. (2003) for *Populus deltoides*, Centritto *et al*. (2004) for *Populus x euroamericana,* and Scholefield *et al*. (2004) for *Phragmites australis*, Possell *et al*. developed a single downward-trending isoprene emissions curve that stretches from 180 to 1,200 ppm CO_2, where it asymptotically approaches a value that is an order of magnitude less than what it is at 180 ppm.

Working at the Biosphere 2 facility near Oracle, Arizona, USA in enclosed ultraviolet light-depleted mesocosms (to minimize isoprene depletion by atmospheric oxidative reactions such as those involving OH), Pegoraro *et al*. (2005) studied the effects of atmospheric CO_2 enrichment (1,200 ppm compared to an ambient concentration of 430 ppm) and drought on the emission of isoprene from cottonwood (*Populus deltoides* Bartr.) foliage and its absorption by the underlying soil for both well-watered and drought conditions. They found "under well-watered conditions in the agriforest stands, gross isoprene production (i.e., the total production flux minus the soil uptake) was inhibited by elevated CO_2 and the highest emission fluxes of isoprene were attained in the lowest CO_2 treatment." The elevated CO_2 treatment resulted in a 46 percent reduction in gross isoprene production. In addition, the researchers found drought suppressed the isoprene sink capacity of the soil beneath the trees, but "the full sink capacity of dry soil was recovered within a few hours upon rewetting."

Putting a slightly negative slant on their findings, Pegoraro *et al*. suggest "in future, potentially hotter, drier environments, higher CO_2 may not mitigate isoprene emission as much as previously suggested." But it should be noted that climate models generally predict an intensification of the hydrologic cycle in response to rising atmospheric CO_2 concentrations, and that the anti-transpirant effect of atmospheric CO_2 enrichment typically leads to increases in the moisture contents of soils beneath vegetation. Over the latter decades of the twentieth century, when the IPCC claims Earth warmed at a rate and to a level unprecedented over the past two millennia, soil moisture data from around the world tended to display upward trends. Robock *et al*. (2000), for example, collected soil moisture data from more than 600 stations across a variety of climatic regimes, determining, "In contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." In a subsequent study of "45 years of gravimetrically observed plant available soil moisture for the top 1 m of soil, observed every 10 days for April–October for 141 stations from fields with either winter or spring cereals from the Ukraine for 1958–2002," Robock *et al*. (2005) found "a positive soil moisture trend for the entire period of observation," noting "even though for the entire period there is a small upward trend in temperature and a downward trend in summer precipitation, the soil moisture still has an upward trend for both winter and summer cereals." A CO_2-enriched world of the future will likely present the best of both aspects of isoprene activity: less production by vegetation and more consumption by soils.

In addressing how well climate models predict the response of isoprene emission to future global change, Monson *et al*. (2007) note such predictions "probably contain large errors" because "the fundamental logic of such models is that changes in NPP [net primary production] will produce more or less biomass capable of emitting isoprene, and changes in climate will stimulate or inhibit emissions per unit of biomass." The 12 researchers continue, "these models tend to ignore the discovery that there are direct effects of changes in the atmospheric CO_2 concentration on isoprene emission that tend to work in the opposite direction to that of stimulated NPP." Their results show, in their words, "that growth in an atmosphere of elevated CO_2 inhibited the emission of isoprene at levels that completely compensate for possible increases in emission due to increases in aboveground NPP." Monson *et al*. state, "to a large extent, the modeling has 'raced ahead' of our mechanistic understanding of how isoprene emissions will respond to the fundamental drivers of global change." They conclude, "without inclusion of these effects in the current array of models being used to predict changes in atmospheric chemistry due to global change, one has to question the relevance of the predictions."

Arneth *et al*. (2008) used a mechanistic isoprene-dynamic vegetation model of European woody vegetation to "investigate the interactive effects of climate and CO_2 concentration on forest productivity, species composition, and isoprene emissions for the periods 1981–2000 and 2081–2100," which included a parameterization of the now-well-established direct CO_2-isoprene inhibition phenomenon described in the studies discussed above. They found "across the model domain," the CO_2-isoprene inhibition effect "has the potential to offset the stimulation of [isoprene] emissions that could be expected from warmer temperatures and from the increased productivity and leaf area of emitting vegetation."

In something of a challenge to this thesis, Kiendler-Scharr *et al*. (2009) "present evidence from simulation experiments conducted in a plant chamber that isoprene can significantly inhibit new particle formation." The significance of this finding, they write, derives from the fact that "the most abundant volatile organic compounds emitted by terrestrial vegetation are isoprene and its derivatives, such as monoterpenes and sesquiterpenes" and that (as described in the "This Issue" abstract section of *Nature* (p. 311)) "these compounds are involved in the formation of organic aerosols [the "new particles" mentioned by them], which act as 'seeds' for cloud formation and hence as cooling agents via an effect on radiative forcing." Moreover, as Ziemann (2009) explained in a "News & Views" article that discusses the Kiendler-Scharr *et al*. paper, "clouds formed at higher CCN [cloud condensation nuclei] concentrations have more and smaller drops than those formed at lower concentrations, and so reflect more sunlight and are longer-lived—effects that, at the global scale, enhance the planetary cooling that counteracts some of the warming caused by greenhouse gases." Thus, if vegetative isoprene emissions were to increase, driven directly by rising temperatures and/or indirectly by warming-induced changes in the species composition of boreal forests (as further suggested by Ziemann), the resulting decrease in CCN concentrations "could lead to increased global-warming trends," as suggested by Kiendler-Sharr in a "Making the Paper" article in the same issue of *Nature* (p. 313).

The story propounded by these facts may seem to deliver a devastating blow to the negative CO_2-induced isoprene feedback, yet, and almost as an afterthought, Ziemann writes consideration also should be given to what he calls "the potential suppression of terpene emissions by elevated carbon dioxide concentrations." When this is done, as demonstrated by the multiple sets of observational data of Young *et al*. (2009) and plotted in Figure 2.5.2.2.1.1, it becomes clear that rising atmospheric CO_2 concentrations will significantly decrease isoprene emissions from plants and thereby increase cloud condensation nuclei concentrations and lead to a cooling of the planet.

Wilkinson *et al*. (2009) grew three-year-old cottonwood trees and two-year-old aspen trees in controlled-environment chambers maintained for several weeks at atmospheric CO_2 concentrations of 400 and 800 ppm, with the aspen trees also exposed to CO_2 concentrations of 600 and 1,200 ppm. In addition, they grew two-year-old sweetgum and eucalyptus trees in another controlled-environment facility maintained at CO_2 concentrations of 240 and 380 ppm. They measured the isoprene emission rate (IS) of the trees' leaves, finding "IS was approximately 30% and 18% lower, respectively, for eucalyptus and sweetgum trees grown at 520 ppm CO_2, compared with trees grown at 240 ppm CO_2." The nine researchers also found the cottonwood and aspen trees "exhibited a 30–40% reduction in isoprene emission rate when grown at 800 ppm CO_2, compared with 400 ppm CO_2," and the aspen trees "exhibited a 33% reduction when grown at 1200 ppm CO_2, compared with 600 ppm CO_2."

Wilkinson *et al*. then "used current models of leaf isoprene emission to demonstrate that significant errors occur if the CO_2 inhibition of isoprene is not taken into account," developing in the process "a quantitative algorithm that can be used to scale IS at the leaf level to changes in atmospheric and intercellular CO_2" that can be "incorporated into larger-scale models that aim to predict regional or global patterns in IS," which can further be used to address "important questions concerning atmospheric chemistry in the face of future global change projections."

In a related paper published in the same issue of *Global Change Biology*, Heald *et al*. (2009) incorporated an empirical model of observed isoprene

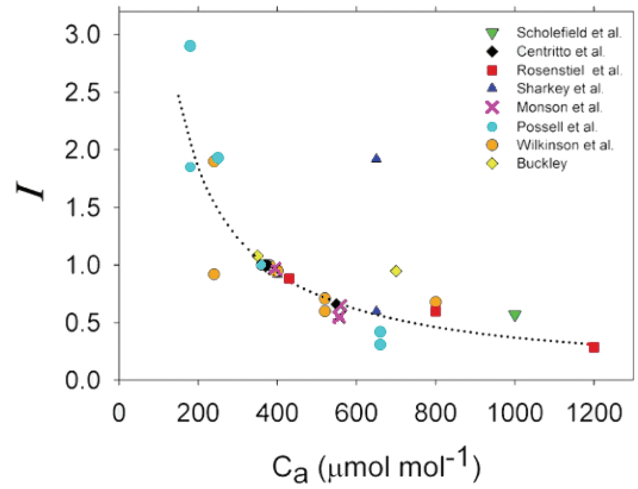

Figure 2.5.2.2.1.1. Field and laboratory observations of leaf isoprene emissions (I) from plants grown in a variety of atmospheric CO_2 concentrations (Ca), normalized to a value of unity at Ca = 370 μmol mol^{-1} (= 370 ppm). Reprinted with permission from Young, P.J., Arneth, A., Schurgers, G., Zeng, G., and Pyle, J.A. 2009. The CO_2 inhibition of terrestrial isoprene emission significantly affects future ozone projections. *Atmospheric Chemistry and Physics* **9**: 2793–2803.

emissions response to changes in atmospheric CO_2 concentration in the long-term growth environment and short-term changes in intercellular CO_2 concentrations into a biogenic emission model embedded within the Community Land Model of the global NCAR Community Climate System Model. They found "the large increases in future isoprene emissions typically predicted in models, which are due to a projected warmer climate, are entirely offset by including the CO_2 effects."

Lathiere *et al*. (2010) utilized the Model of Emissions of Gases and Aerosols from Nature (MEGAN), developed by Guenther *et al*. (2006), to calculate changes in isoprene emissions from the terrestrial biosphere in response to climate change, atmospheric CO_2 increase, and land use change throughout the twentieth century. They found between 1901 and 2002, climate change at the global scale "was responsible for a 7% increase in isoprene emissions," but "rising atmospheric CO_2 caused a 21% reduction," and "by the end of the 20th century, anthropogenic cropland expansion had the largest impact, reducing isoprene emissions by 15%." As a result, "overall, these factors combined to cause a 24% decrease in global isoprene emissions during the 20th century." The three scientists also warned "the possible rapid expansion of biofuel production with high isoprene-emitting plant species (e.g., oil palm, willow and poplar) may reverse the trend by which conversion of land to food crops leads to lower isoprene emissions."

The research reviewed here strongly suggests the ongoing rise in atmospheric CO_2 concentrations will reduce atmospheric isoprene concentrations, which will lead to increases in cloud condensation nuclei concentrations, ultimately leading to a cooling of the planet—a negative feedback ignored by most proponents of the CO_2-induced global warming theory.

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2.5.3 Non-Biological

2.5.3.1 Anthropogenic

There are several ways the activities of humanity lead to the creation of aerosols that have the potential to alter Earth's radiation balance and affect its climate. Contrails created in the wake of emissions from jet aircraft are one example. Minnis *et al*. (2004) have calculated nearly all of the surface warming observed over the United States between 1975 and 1994 (0.54°C) may be explained by aircraft-induced increases in cirrus cloud coverage over that period. If true, this would imply little or none of the observed U.S. warming during that period could be attributed to the increase in the air's CO_2 content.

Ship tracks—bright streaks that form in layers of marine stratus clouds—are another example. Created by emissions from ocean-going vessels, these persistent and highly reflective linear patches of low-level clouds tend to cool the planet (Ferek *et al*., 1998; Schreier *et al*., 2006).

Schreier *et al*. (2006) developed an algorithm "to determine ship tracks from satellite data in an automated way," after which "a scene on 10 February 2003 was chosen to extract the optical and microphysical cloud modifications from ship emissions using Terra-MODIS satellite data," in which "a combination of the semi-analytical approach SACURA [Kokhanovsky *et al*., 2003] with a look-up-table for optically thin clouds [Mayer and Kylling, 2005] was used to calculate cloud properties." The analysis revealed, on average, cloud "optical thickness was increased from 20.7 up to 34.6 and the effective [droplet] radius was decreased from 13.2 µm to 10.1 µm," while "the calculated average droplet number concentration increased from 79 up to 210 cm^{-3}."

Using these numbers to calculate changes in the radiative energy budget above and below the marine stratus clouds influenced by the ship emissions, Schreier *et al*. (2006) reported "a decrease of 43.2 W m^{-2} for the surface radiation below the ship tracks and an increase of 40.8 W m^{-2} for the increased reflectivity at the top of the atmosphere." They note, "if the whole low-cloud area with 6.7% ship-track-pixels is taken into account, a decrease in the radiation at the surface of 2.1 W m^{-2} and an increase of 2.0 W m^{-2} in backscattered solar radiation [is] found." The eight German researchers thus conclude, "modifications of clouds by international shipping can be an important contributor to climate on a local scale."

As for the global scale, averaged over the surface of Earth both day and night and over the year, Capaldo *et al*. (1999) calculated this phenomenon creates a mean negative radiative forcing of -0.16 W m^{-2} in the Northern Hemisphere and -0.06 W m^{-2} in the Southern Hemisphere. Compare these values to a much smaller estimate from the IPCC (compare the W m^{-2} with the mW m^{-2} unit), which concluded in its most recent assessment, "the global radiative forcing of visible ship tracks has been estimated from satellite and found to be insignificant at about -0.5 mW m^{-2}" (p. 7-39 of Chapter 7, Second Order Draft of AR5, dated October 5, 2012). For additional context, the IPCC calculates a positive radiative forcing of approximately 4 W m^{-2} due to a 300 ppm increase in the atmosphere's CO_2 concentration.

In some cases, the atmosphere over the sea also carries a considerable burden of anthropogenically produced aerosols from terrestrial sites. In recent years, attention to this topic has centered on highly polluted air from south and southeast Asia that makes its way over the northern Indian Ocean during the dry monsoon season. There has been much discussion about the impact of this phenomenon on regional climates. Norris (2001) looked at cloud cover as the ultimate arbiter of the competing hypotheses, finding daytime low-level oceanic cloud cover increased substantially over the last half of the past century in both the Northern and Southern Hemispheres at essentially all hours of the day. This finding is indicative of a pervasive net cooling effect.

Aerosol-generating human activities also have a significant impact on local, as well as more wide-ranging, climatic phenomena over land. Sahai (1998) pointed out although suburban areas of Nagpur, India had warmed over recent decades, the central part of the city had cooled, especially during the day, because of "increasing concentrations of suspended particulate matter." Similarly, outside but adjacent to industrial complexes in the Po Valley of Italy, Facchini *et al*. (1999) found water vapor was more likely to form on aerosols altered by human-produced organic solutes, and this phenomenon led to the creation of more numerous and more highly reflective cloud droplets that had a tendency to cool the surface below them.

Rosenfeld (2000) studied pollution tracks downwind of urban/industrial complexes in Turkey, Canada, and Australia. His findings indicate the clouds comprising these pollution tracks were composed of small droplets that suppressed precipitation by inhibiting further coalescence and ice precipitation formation. In commenting on this research, Toon (2000) notes when clouds are composed of smaller droplets, they will not "rain out" as quickly and therefore will last longer and cover more of Earth, both of which effects tend to cool the globe.

In reviewing these and other advances in the field of anthropogenic aerosol impacts on clouds, Charlson *et al*. (2001) note droplet clouds "are the most important factor controlling the albedo (reflectivity) and hence the temperature of our planet." They also note manmade aerosols "have a strong influence on cloud albedo, with a global mean forcing estimated to be of the same order (but opposite in sign) as that of greenhouse gases" and "both the forcing [of this impetus for cooling] and its magnitude may be even larger than anticipated." Failure to include these important phenomena in climate change deliberations "poses additional uncertainty beyond that already recognized by the Intergovernmental Panel on Climate Change, making the largest uncertainty in estimating climate forcing even larger."

Devasthale *et al*. (2005) examine the possible influence of aerosols on cloud-top temperature (CTT) using long-term satellite brightness temperatures from the Advanced Very High Resolution Radiometer onboard the NOAA satellite series over eastern and central Europe. In order to identify and quantify possible aerosol-induced changes, CTTs were compared for two four-year periods of distinctively higher (1985–1998) and lower (1997–2000) anthropogenic pollution loads.

Devasthale *et al*. report the results of the analysis were "astonishing." For all types and levels of clouds analyzed, over both land and sea, lower CTTs were observed during the higher pollution levels of the late 1980s, such that the tops of low- and medium-level clouds were more than 2°C colder during that period, and about 4°C colder if convective clouds were included. Regions of greater CTT variability coincided with metropolitan areas and industrial centers that contained higher concentrations of particulate matter and black carbon inventories.

One implication of these findings, the researchers noted, is the "observed indirect aerosol effect in the thermal infrared on regional scale could be equally important if not dominant over the solar radiation changes and thus needs to be further investigated for other regions." This effect may be large enough to have had a significant influence on the near-surface and tropospheric temperature histories of the past few decades.

Another pertinent observation comes from Stanhill and Cohen (2001), who reviewed numerous solar radiation measurement programs around the world to see if there had been any trend in the mean amount of solar radiation falling on the surface of Earth over the past half-century. They determined there was a significant 50-year downward trend in this parameter that "has globally averaged 0.51 ± 0.05 W m^{-2} per year, equivalent to a reduction of 2.7 percent per decade, [which] now totals 20 W m^{-2}." They conclude the most probable explanation for this observation "is that increases in man-made aerosols and other air pollutants have changed the optical properties of the atmosphere, in particular those of clouds."

This surface-cooling influence falls in the mid-range of a similar solar radiative perturbation documented by Satheesh and Ramanathan (2000) in their study of the effects of human-induced pollution over the tropical northern Indian Ocean, where they determined "mean clear-sky solar radiative heating for the winters of 1998 and 1999 decreased at the ocean surface by 12 to 30 W m^{-2}." Hence, the decline in solar radiation reception discovered by Stanhill and Cohen could well be real, representing a strong counter-influence to the enhanced greenhouse effect produced by the increase in atmospheric CO_2 concentration.

Alpert *et al*. (2005) hypothesized the dimming of the 1950s through 1980s could be explained by the anthropogenic release of pollutants, such as sulfates, nitrates, and black carbon, which acted to reduce the amount of solar radiation received at Earth's surface. To test this theory, for the 25-year period 1964–1989 the authors examined trends in the surface receipt of solar radiation at 144 urban sites (population greater than 100,000 persons) and 174 rural sites (population less than 100,000 persons) for various latitudinal bands as well as for the entire globe. For the globe as a whole, they found both urban and rural locations showed a decline in surface solar radiation over the period of study. The rate of decline at the urban locations was approximately 2.6 times larger than that observed at the rural locations (-0.41 W $m^{-2}yr^{-1}$ vs. -0.16 W $m^{-2}yr^{-1}$). In addition, a sharper decline in surface solar radiation receipt was found between 10°N and 40°N, the latitudinal zone nearly coincident with the zone of maximum fossil fuel emissions in the Northern Hemisphere reported by Stanhill and Cohen (2001) for the period 1960–1990. The latitude band from 15°S to 15°N displayed the opposite trend: Instead of dimming, this region experienced a brightening of 0.58 W $m^{-2}yr^{-1}$, a finding consistent with those of Pinker *et al*. (2005), who reported a persistent increase in surface solar radiation over the latitudes 20°S to 20°N based on satellite data.

According to Alpert *et al*., their findings suggest solar dimming is "significantly dominated by large cities' contributions to the atmospheric pollution" and it is "essentially a local phenomenon, observed only in a limited part of the total land area." The magnitudes of the original dimming and the more recent brightening are much greater than the magnitude of the increase in total greenhouse-gas-induced radiative forcing over this period, yet another good reason to suggest the global instrumental temperature record may be significantly "polluted" in a way that has heretofore not been adequately appreciated.

In a more recent study, Ruckstuhl *et al*. (2008) presented "observational evidence of a strong decline in aerosol optical depth over mainland Europe during the last two decades of rapid warming"—when air temperatures rose by about 1°C after 1980—via analyses of "aerosol optical depth measurements from six specific locations and surface irradiance measurements from a large number of radiation sites in Northern Germany and Switzerland." They observed a decline in aerosol concentration of up to 60 percent and found "a statistically significant increase of solar irradiance under cloud-free skies since the 1980s." The value of the direct aerosol effect of this radiative forcing was approximately 0.84 W m^{-2}; when combined with the concomitant cloud-induced radiative forcing of about 0.16 W m^{-2}, it led to a total radiative surface climate forcing over mainland Europe of about 1 W m^{-2} that "most probably strongly contributed to the recent rapid warming in Europe." Cleaning up significantly polluted skies, it seems, can provide an even greater impetus for climate warming than does the carbon dioxide concurrently emitted to them.

Mission *et al*. (2005) note "anthropogenic aerosols have more efficient optical extinction for light than natural aerosols (Carrico *et al*., 2003; Seinfeld and Pandis, 1998) and are responsible for about half of the extinction and scattering of light by particles globally (Houghton *et al*., 2001)." Increases in atmospheric aerosols, while reducing the total flux of solar radiation received at Earth's surface, increase the flux of *diffuse* light received there, such that the volume of shade within forest canopies is so greatly decreased it enhances whole-canopy photosynthesis to the point that more CO_2 is extracted from the atmosphere under high-aerosol-content conditions than under more pristine conditions (see, for example, the work of Roderick *et al*. (2001), Law *et al*. (2002), and Gu *et al*. (2003)).

Mission *et al*. determined the recurrent influx of air pollution from California's Central Valley to the Blodgett Forest site during summer afternoons decreased total irradiance there by 11 percent from what it was at comparable times relative to solar noon in the mornings. Diffuse radiation, on the other hand, was 24 percent higher in the afternoons; this effect predominated to the extent that "aerosol loading caused net uptake of CO_2 by the forest to increase by 8% in the afternoon." The presence of atmospheric aerosols not only reduces the receipt of solar radiation at Earth's surface, providing an impetus for cooling, it also enhances forest rates-of-removal of CO_2 from the atmosphere, which over the long term provides yet another cooling effect.

Su *et al*. (2011) describe and demonstrated how reactive nitrogen compounds, such as those found in synthetic fertilizers, may be acted upon by soil microbes to produce nitrites in both agricultural soils and the soils of forests and boreal regions; and they show how the photolysis of the nitrous acid (HONO) consequently found in these soils can produce up to ~30 percent of the atmosphere's total OH concentration. Their findings explain the origin, size, and diurnal variation of field observations that had previously suggested there was a large unknown source of HONO having the characteristics they identified.

The phenomenon described by the ten scientists plays an important role in the atmosphere's photochemistry, which in turn plays a key role in the planet's energy balance, because OH radicals act as precursors of aerosols that can contribute to climate change by reflecting a portion of the incoming solar radiation from the Sun back to space, thereby exerting a cooling influence on the planet. To quote the international team of researchers, "because of enhanced fertilizer use and soil acidification in developing countries (Guo *et al*., 2010), the release of HONO from soil nitrite might strongly increase in the course of global change, resulting in elevated OH concentrations and amplified oxidizing capacity of the lower troposphere," which would tend to impede the warming that helped to initiate the phenomenon, illustrating yet another of the "checks and balances" built into Earth's highly complex climatic system.

In further commentary on Su *et al*.'s findings, Kulmala and Petaja (2011) rhetorically asked: "What would happen if global HONO emissions from soil doubled within the next 25 years?" In answer, they said it "could increase the atmosphere's ability to cleanse itself of volatile compounds such as methane," a powerful greenhouse gas. Perhaps that is why atmospheric methane concentrations have risen at a much slower rate over the prior two decades than they had previously risen, as has been reported by Simpson *et al*. (2002), Dlugokencky *et al*. (2003), Khalil *et al*. (2007), Schnell and Dlugokencky (2008), and other researchers.

Anthropogenic aerosols clearly affect climate in ways that rival or even exceed the likely effect of rising atmospheric CO_2 levels. As great progress has been made in recent decades to reduce air pollution in developed countries, it is entirely possible the lion's share of warming has been produced by the removal from the atmosphere of true air pollutants.

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2.5.3.1.1 Black Carbon

Kaspari *et al*. (2011) point out "black carbon (BC, the absorbing component of soot) produced by the incomplete combustion of biomass, coal and diesel fuels can significantly contribute to climate change by altering the Earth's radiative balance," noting "BC is estimated to have 55% of the radiative forcing effect of CO_2 (Ramanathan and Carmichael, 2008)," in line with the approximately 1 W m^{-2} radiative forcing of black carbon reported by Hansen (2002).

Kaspari *et al*. further note BC remains "one of the largest sources of uncertainty in analyses of climate change." They developed a high-resolution BC record spanning the period AD 1860–2000 from a Mt. Everest ice core extracted from the East Rongbuk glacier located on the mountain's northeast ridge on the north slope of the Himalaya, which record, in their words, "provides the first pre-industrial-to-present record of BC concentrations from the Himalayas." The seven scientists determined "BC concentrations from 1975–2000 relative to 1860–1975 have increased approximately threefold, indicating that BC from anthropogenic sources is being transported to high elevation regions of the Himalaya." In addition, "the increase in Everest BC during the 1970s is simultaneous with a rise in BC emissions as estimated from historical records of energy-related combustion in South Asia and the Middle East (Bond *et al*., 2007)."

Kaspari *et al*. said their findings suggest "a reduction in BC emissions may be an effective means to reduce the effect of absorbing impurities on snow albedo and melt, which affects Himalayan glaciers and the availability of water resources in major Asian rivers." Ramanathan and Carmichael (2008) note the majority of BC emissions (60 percent) arise from "cooking with biofuels such as wood, dung and crop residue" and from "open biomass burning (associated with deforestation and crop residue burning)," while Venkataraman *et al*. (2005) note control of BC emissions through cleaner cooking technologies alone could help in "reducing health risks to several hundred million users." It would seem reducing biofuel sources of BC emissions would be a prudent goal.

Also working in Asia, Kopacz *et al*. (2011) point out "the Himalayas and the Tibetan Plateau, also collectively known as the Third Pole, represent a large area of seasonal and permanent snow cover," which is "surrounded by growing emissions of Asian air pollutants." They note observations of black carbon (BC) content in snow "show a rapidly increasing trend," citing the work of Xu *et al*. (2009). For their own study of the subject, Kopacz *et al*. used a global chemical transport model to identify the location from which the BC arriving at a variety of locations in the Himalayas and the Tibetan Plateau originates, after which they calculated its direct and snow-albedo radiative forcings.

According to the six U.S. scientists, the results indicated "emissions from northern India and central China contribute the majority of BC to the Himalayas," and "the Tibetan Plateau receives most BC from western and central China, as well as from India, Nepal, the Middle East, Pakistan and other countries." In addition, they report the radiative forcing due to the direct effect of BC at five glacier sites has "a global annual mean of +0.32 W/m^2, while "the local monthly mean radiative forcing due to changes in snow-albedo ranges from +3.78 to +15.6 W/m^2."

Researching a much larger region of the globe, for the period 1875–2000, Novakov *et al*. (2003) presented "estimates of past fossil-fuel BC emissions from the United States, United Kingdom, Germany, Soviet Union, India and China," which nations in 1990 accounted for "about 70% and 60%, respectively, of the world consumption of coal and diesel fuel, which are the principal BC-producing fossil-fuels." The authors report a "rapid increase [in BC] in the latter part of the 1800s, ... leveling off in the first half of the 1900s, and … re-acceleration in the past 50 years as China and India developed." They estimate the climate forcing by BC aerosols to be "of the order of +0.5 W m^{-2}," two-thirds greater than the +0.3 W m^{-2} forcing estimate of the IPCC (p. 18 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). They also note "estimates of the current anthropogenic BC climate forcing are of the order of 1/3 to 1/2 of the current CO_2 forcing."

It is apparent that modern trends in BC have presented a significant radiative forcing across many parts of the globe meriting serious examination and future study, especially by the IPCC, in order to correctly interpret past, present, and future climate trends.

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2.5.3.2 Natural

We conclude this section with a brief discussion of a non-biological, naturally produced aerosol: dust.

Dust is about as natural and ubiquitous a substance as there is. One might expect scientists to have a pretty good handle on what it does to Earth's climate, but that is not the case.

Sokolik (1999), with the help of nine colleagues, summarized the sentiments of a number of scientists who had devoted their lives to studying the subject. According to Sokolik, state-of-the-art climate models "rely heavily on oversimplified parameterizations" of many important dust-related phenomena, "while ignoring others." As a result, Sokolik concludes "the magnitude and even the sign of dust net direct radiative forcing of climate remains unclear."

Sokolik says there are a number of unanswered questions about airborne dust: How does one quantify dust emission rates from natural and anthropogenic sources with required levels of temporal and spatial resolution? How does one accurately determine the composition, size, and shape of dust particles from ground-based and aircraft measurements? How does one adequately measure and model light absorption by mineral particles? How does one link the ever-evolving optical, chemical, and physical properties of dust to its life cycle in the air? How does one model complex multi-layered aerosol stratification in the dust-laden atmosphere? And how does one quantify airborne dust properties from satellite observations?

In discussing these questions, Sokolik observed what is currently known, or believed to be known, about dust emissions "is largely from micro-scale experiments and theoretical studies." He suggests new global data sets are needed to provide "missing information" on input parameters (such as soil type, surface roughness, and soil moisture) required to model dust emission rates, and improvements in methods used to determine some of these parameters are also "sorely needed." How to adequately measure light absorption by mineral particles is an "outstanding problem," he notes, and it "remains unknown how well these measurements represent the light absorption by aerosol particles suspended in the atmosphere." It is easy to understand why Sokolik concludes "a challenge remains in relating dust climatology and the processes controlling the evolution of dust at all relevant spatial/temporal scales needed for chemistry and climate models."

Vogelmann *et al*. (2003) reiterated that "mineral aerosols have complex, highly varied optical properties that, for equal loadings, can cause differences in the surface IR flux [of] between 7 and 25 W m^{-2} (Sokolik *et al*., 1998)," while at the same time acknowledging "only a few large-scale climate models currently consider aerosol IR effects (e.g., Tegen *et al*., 1996; Jacobson, 2001) despite their potentially large forcing." Vogelmann *et al*. "use[d] high-resolution spectra to obtain the IR radiative forcing at the surface for aerosols encountered in the outflow from northeastern Asia," based on measurements made by the Marine-Atmospheric Emitted Radiance Interferometer aboard the NOAA Ship *Ronald H. Brown* during the Aerosol Characterization Experiment-Asia. This work led them to conclude, "daytime surface IR forcings are often a few W m^{-2} and can reach almost 10 W m^{-2} for large aerosol loadings," which values, in their words, "are comparable to or larger than the 1 to 2 W m^{-2} change in the globally averaged surface IR forcing caused by greenhouse gas increases since pre-industrial times." Vogelmann *et al*. conclude their results "highlight the importance of aerosol IR forcing which should be included in climate model simulations."

Another aspect of the dust-climate connection centers on the African Sahel, which has figured prominently in discussions of climate change since it began to experience extended drought conditions in the late 1960s and early '70s. Initial studies of the drought attributed it to anthropogenic factors such as overgrazing of the region's fragile grasses, which tends to increase surface albedo, which was envisioned to reduce precipitation, resulting in a further reduction in the region's vegetative cover (Otterman, 1974; Charney, 1975). That scenario was challenged by Jackson and Idso (1975) and Idso (1977) on the basis of empirical observations, while Lamb (1978) and Folland *et al*. (1986) attributed the drought to large-scale atmospheric circulation changes triggered by multidecadal variations in sea surface temperature.

Building on the insights provided by these latter investigations, Giannini *et al*. (2003) presented evidence based on an ensemble of integrations with a general circulation model of the atmosphere—forced only by the observed record of sea surface temperature—which suggests the "variability of rainfall in the Sahel results from the response of the African summer monsoon to oceanic forcing amplified by land-atmosphere interaction." The success of this analysis led them to attribute "the recent drying trend in the semi-arid Sahel … to warmer-than-average low-latitude waters around Africa, which, by favoring the establishment of deep convection over the ocean, weaken the continental convergence associated with the monsoon and engender widespread drought from Senegal to Ethiopia." They further conclude "the secular change in Sahel rainfall during the past century was not a direct consequence of regional environmental change, anthropogenic in nature or otherwise."

In a companion article, Prospero and Lamb (2003) report measurements made from 1965 to 1998 in the Barbados trade winds show large interannual changes in the concentration of dust of African origin that are highly anticorrelated with the prior year's rainfall in the Soudano-Sahel. They noted the 2001 IPCC report "assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts." But "there is little firm evidence to support either of these assumptions," they write.

Huang *et al*. (2011) calculated bulk sediment fluxes and analyzed grain-size distributions of detrital sediments over the past two millennia from an 11.12 meter sediment core obtained from Asia's Aral Sea, after which they compared their results with the temperature history of the Northern Hemisphere produced by Mann and Jones (2003), with an emphasis "placed on the variations at the transition from the Medieval Warm Period (MWP) to Little Ice Age (LIA) since this period is the most pronounced climatic transformation during the last millennium," citing in this regard the studies of Yang *et al*. (2002), Trouet *et al*. (2009), and Chen *et al*. (2010).

The comparison revealed "a remarkably low deposition [of dust] during AD 1–350," which would have been part of the Roman Warm Period; "a moderately high value from AD 350–720," which corresponds to the Dark Ages Cold Period; "a return to a relatively low level between AD 720 and AD 1400," which includes the Medieval Warm Period; "an exceptionally high deposition from AD 1400 to the 1940s," which includes the Little Ice Age; and what they refer to as "an abnormally low value since the 1940s," when the Current Warm Period may be considered to have begun.

The four researchers state the temporal variations in the dust deposition are consistent with changes in the "mean atmospheric temperature of the northern hemisphere during the past 2000 years, with low/high annual temperature anomalies corresponding to high/low dust supplies in the Aral Sea sediments, respectively," reinforcing the reality of a non-CO_2-induced forcing of Earth's surface air temperature.

Clearly, much remains to be learned about the climatic impacts of dust, whose radiative impacts, the IPCC has concluded, "are too uncertain" to include in their estimates of radiative forcing (p. 18 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

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2.6 Other Forcings and Feedbacks

Researchers have identified other forcings and feedbacks about which little is currently known, or acknowledged by the IPCC, but which may ultimately prove to be important drivers of climate change. Other variables, currently considered insignificant, may with changing conditions become important as thresholds change. This section explores some of those phenomena described in the peer-reviewed scientific literature.

2.6.1 Carbon Sequestration

As the carbon dioxide content of the air continues to rise, nearly all of Earth's plants will respond by increasing their photosynthetic rates and producing more biomass. These increases in productivity will likely lead to greater amounts of carbon sequestration in both above- and below-ground plant parts as well as in soils. But how powerful is the carbon sequestering ability of Earth's vegetation? Is it powerful enough to slow the rise of atmospheric CO_2 to provide a natural brake on CO_2-induced global warming? How is it affected by an increase in air temperature? This section reviews the results of studies that have addressed these and other important questions pertaining to biospheric carbon sequestration.

Early investigation into this topic occurred more than two decades ago when many people were concerned the air's CO_2 content would rise in direct proportion to the magnitude of humanity's increasing emissions of carbon dioxide. Idso (1991a,b) felt otherwise and predicted the air's CO_2 content would rise at a rate that would be a declining percentage of anthropogenic CO_2 emissions, hypothesizing the productivity of Earth's plant life would rise in response to the ongoing increase in the air's CO_2 content—due to the well-known aerial fertilization effect of carbon dioxide—thereby resulting in ever more CO_2 being removed from the atmosphere each year. Vindication of Idso's thesis came via real-world data a decade later, with Wofsy (2001) reporting in a "Climate Change" article in *Science* that "emission rates of CO_2 from combustion of fossil fuel have increased almost 40 percent in the past 20 years, but the amount of CO_2 accumulating in the atmosphere has stayed the same or even declined slightly."

Other studies also have demonstrated this increased ability of the biosphere to sequester carbon from the atmosphere as the air's CO_2 concentration has gradually risen over the past few decades and throughout the Industrial Revolution. Working in the coterminous United States, for example, Pacala *et al*. (2001) found estimates of the country's 48-state carbon sequestering power have grown significantly over the past several years, from a range of 0.08–0.35 x 10^{15} grams of carbon per year (Pg C yr^{-1}) in the 1980s to a range of 0.37–0.71 Pg C yr^{-1} by the turn of the century, with some evidence suggesting values as high as 0.81–0.84 Pg C yr^{-1} (Fan *et al*., 1998).

Similarly, Fang *et al*. (2001) reported increases in carbon sequestration in China. With a little help from the Chinese government via several "ecological restoration projects" aimed primarily at afforestation and reforestation, the world's most populous country has turned around what had been a losing proposition with respect to carbon capture by forests, where an average of 0.021 Pg C yr^{-1} had been sequestered there for about the last two decades of their study.

Harrison *et al*. (2008) used the Joint UK Land Environment Simulator (JULES), a land surface and carbon cycle model, to simulate the biospheric carbon balance of Europe and its sensitivity to rising CO_2 and changes in climate experienced over the period 1948–2005. Over the 57-year period of their study, Harrison *et al*. report "the impact of climate changes since 1948 has been to decrease the ability of Europe to store carbon by 97 TgC $year^{-1}$," but "the effect of rising atmospheric CO_2 has been to stimulate increased uptake and storage." This latter phenomenon apparently was so strong it led, in their words, to "a net increase in stored carbon of 114 TgC $year^{-1}$."

In addition to stimulating *terrestrial* carbon storage, the rising atmospheric CO_2 concentration also should enhance *oceanic* carbon sequestration. Wolf-Gladrow *et al*. (1999) reviewed the direct effects of atmospheric CO_2 enrichment on marine biota and oceanic "carbon pumps," concluding an increase in the air's CO_2 content should increase the capacity of Earth's oceans to take up and store more atmospheric CO_2.

Working on both fronts (land and ocean), Joos and Bruno (1998) utilized ice cores and direct observations of atmospheric CO_2 and ^{13}C to reconstruct the histories of terrestrial and oceanic uptake of anthropogenic carbon over the past two centuries. During the initial portion of this period and persisting into the first decades of the past century, they determined the biosphere as a whole supplied carbon to the atmosphere. Thereafter, however, the biosphere became a carbon sink. In further scrutinizing their data, they note the current global carbon sink has been growing in magnitude for at least the past hundred years.

In reviewing the progress of research dealing with the global carbon cycle, Tans and White (1998) conclude "early estimates of huge losses of carbon from plants and soils due to biomass burning and deforestation have recently given way to the idea of a terrestrial biosphere nearly balanced (globally) with respect to carbon." After analyzing O_2/N_2 measurements of background air collected at Cape Grim, Tasmania from 1978 to 1997, Langenfelds *et al*. (1999) determined the surface fluxes of carbon over this 19-year period were "essentially in balance." In other words, essentially all of the carbon released to the air as a consequence of the activities of man was removed from the atmosphere by the biological activities of predominantly terrestrial vegetation.

Khatiwala *et al*. (2009) note the world's oceans play "a crucial role in mitigating the effects of [rising

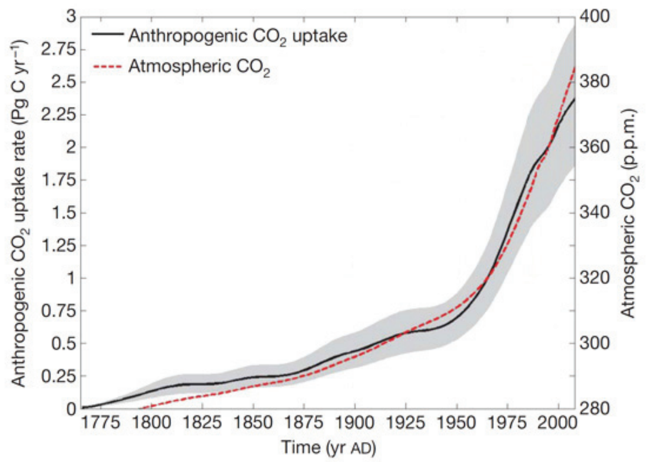

Figure 2.6.1.1. Atmospheric CO_2 concentration and oceanic uptake rate of anthropogenic carbon (with shaded error envelope) plotted against time. Adapted from Khatiwala, S. Primeau, F., and Hall, T. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* **462**: 346–349.

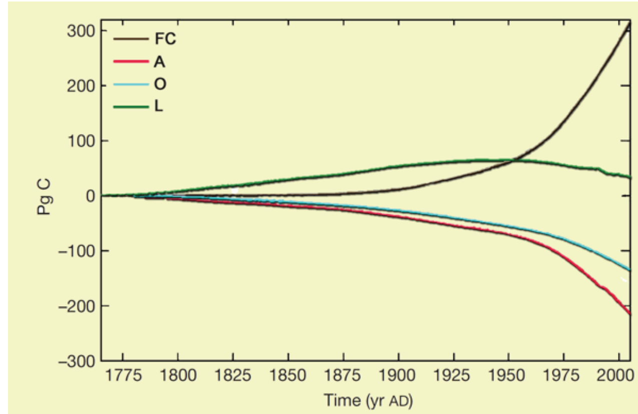

Figure 2.6.1.2. The evolution of anthropogenic-produced carbon originating from fossil fuel use and cement production (FC), together with the similar evolution of the three anthropogenic carbon sinks—atmosphere (A), ocean (O), and land (L)—between AD 1765 and 2005. Adapted from Khatiwala, S. Primeau, F., and Hall, T. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* **462**: 346–349.

atmospheric CO_2] to the climate system." They derived "an observationally based reconstruction of the spatially-resolved, time-dependent history of anthropogenic carbon in the ocean over the industrial era [AD 1765 to AD 2008]," based on the known history of the air's CO_2 concentration and analyses of the oceanic transport of "a suite of well sampled oceanic tracers such as chlorofluorocarbons, natural ^{14}C, temperature, and salinity from the GLODAP and World Ocean Atlas databases." The three U.S. researchers determined the amount of anthropogenic CO_2 taken up by the world's oceans has been increasing with the passage of time, pretty much in phase with the atmosphere's ever-increasing CO_2 concentration, as shown in Figure 2.6.1.1.

In addition, Khatiwala *et al*. note after the sharp increase in the anthropogenic CO_2 uptake rate after the 1950s there has been "a small decline in the rate of increase in the last few decades." This latest deviation of the oceanic CO_2 uptake rate (from its correlation with the atmosphere's CO_2 concentration) is similar to those of prior such deviations, which have been of both a positive and negative nature. The size of the error envelope (the shaded area in Figure 2.6.1.1) associated with the anthropogenic CO_2 uptake rate allows for the possibility that its correlation with the atmosphere's CO_2 concentration could have been essentially perfect from about the 1860s through and including the present time.

Writing about Khatiwala *et al*.'s work in the November 19, 2009 issue of *The New York Times*, Sindya Bhanoo presented a distinctly pessimistic slant to the scientists' findings, stating the growth in the ocean's uptake rate of anthropogenic carbon "has slowed since the 1980s, and markedly so since 2000," implying "the research suggests that the seas cannot indefinitely be considered a reliable 'carbon sink' as humans generate heat-trapping gases." Bhanoo quotes Khatiwala himself as saying the recent trend to lower values of the ocean's uptake rate of anthropogenic carbon "implies that more of the emissions will remain in the atmosphere."

Quite to the contrary, however, the finely intertwined relationship of the two parameters of Figure 2.6.1.1 clearly demonstrates, well within the accuracy of the various measurements involved, that the global ocean is constantly adjusting its uptake rate of anthropogenic carbon on multi-decadal time scales to "keep up" with the rate at which the air's CO_2 content rises in response to anthropogenic carbon inputs.

In light of their independent assessment of the absorption of anthropogenic CO_2 by the global ocean, and knowing the historical record of fossil fuel use and cement production as well as the concomitant change in the atmosphere's CO_2 content, Khatiwala *et al*. also calculated, as a residual, the net absorption of anthropogenic CO_2 by Earth's land surface since the inception of the Industrial Revolution; this latter calculation is presented in Figure 2.6.1.2.

The authors' results indicate "the terrestrial biosphere was a source of anthropogenic carbon until the 1940s, roughly in line with previous model-based estimates, after which it turned into a sink of anthropogenic CO_2." Between the 1980s and 2000s, the strength of the global land sink grew from a value of 0.3 Pg C per year to 1.1 Pg C per year, suggesting the terrestrial biosphere has begun to "flex its muscles," likely in response to the aerial fertilization and transpiration-reducing effects of the ongoing rise in the air's CO_2 content. Others have challenged these findings, suggesting the world's oceans and terrestrial ecosystems may be gradually losing their ability to sequester CO_2 emissions (Canadell *et al*., 2007; Le Quere *et al*., 2007; Schuster and Watson, 2007).

Le Quere *et al*. (2009), for example, developed "a global CO_2 budget for each year during 1959–2008 and analyzed the underlying drivers of each component." In this undertaking, they say "the global increase in atmospheric CO_2 was determined directly from measurements, CO_2 emissions from fossil fuel combustion were estimated on the basis of countries' energy statistics, [while] CO_2 emissions from land-use change were estimated using deforestation and other land-use data, fire observations from space, and assumptions on the carbon density of vegetation and soils and the fate of carbon." For the time evolution of the land and ocean CO_2 sinks, they used "state-of-the-art models on which [they] imposed the observed meteorological conditions of the past few decades."

Le Quere *et al*. reported, "between 1959 and 2008, 43% of each year's CO_2 emissions remained in the atmosphere on average" and "the rest was absorbed by carbon sinks on land and in the oceans." They write, "in the past 50 years, the fraction of CO_2 emissions that remains in the atmosphere each year has likely increased, from about 40% to 45%," stating "models suggest that this trend was caused by a decrease in the uptake of CO_2 by the carbon sinks in response to climate change and variability."

Although their findings can be interpreted as indicating the uptake rate of anthropogenic CO_2 by the oceans, land, or both may have decreased with time—as they and others have suggested—they temper this conclusion with the caveat that "changes in the CO_2 sinks are highly uncertain." It should be noted that the time evolution or temporal histories of the anthropogenic CO_2 sinks in Le Quere *et al*.'s analysis were obtained from models; they themselves admit "sink processes not considered in current models may be contributing to the observed changes" and these "sink processes" would be doing so in unknown ways not included in their calculations. In addition, the work of Khatiwala *et al*. (2009), which covers a longer span of time, reveals the existence of multidecadal variability that in a short half-century context could be interpreted as a trend, but in a much longer two-and-a-half century timeframe is readily recognized as an oscillatory variation about an essentially constant mean.

Knorr (2009) also covered a much longer time-span than Le Quere *et al*., utilizing data on CO_2 emissions arising from fossil-fuel use, cement production, and changes in land use, as well as atmospheric CO_2 concentrations measured at Mauna Loa and the South Pole and those derived from Law Dome and Siple ice-core data, together with their associated uncertainties, to construct a history since 1850 of the airborne fraction of anthropogenic CO_2. The U.K. researcher reports, "despite the predictions of coupled climate-carbon cycle models, no trend in the airborne fraction can be found." He writes in the concluding section of his study, "the hypothesis of a recent or secular trend in the AF cannot be supported on the basis of the available data and its accuracy," indicating not only has the global ocean been increasing its uptake of anthropogenic carbon in such a way as to "keep up" with the rate at which the air's CO_2 content has risen—as has been demonstrated by Khatiwala *et al*. (2009)—so also have Earth's terrestrial ecosystems been "keeping up" in this regard.

Gloor *et al*. (2010) note Canadell *et al*. (2007) and Raupach *et al*. (2008) claimed to have detected a long-term increasing trend in the airborne fraction that they interpret as being indicative of "a decreasing trend in the efficiency of the ocean and land carbon sinks." Noting Knorr (2009) had already challenged Canadell *et al*. and Raupach *et al*. with respect to their detection of a positive AF trend, "arguing that given the noise in the data, the trend is not detectable," Gloor *et al*. (2010) proceeded to challenge the second claim of Canadell *et al*. and Raupach *et al*.; i.e., their contention that a positive AF trend is indicative of decreasing planetary carbon sink efficiency, by investigating "the question of what controls trends and decadal scale variations in CO_2 airborne fraction using simple linear models describing the evolution of an atmospheric perturbation in CO_2."

The three researchers first determined there is no one-to-one association between positive trends in CO_2 flux to the atmosphere due to fossil fuel emissions and changes in land use and negative trends in Earth's carbon sink efficiency. Secondly, they found that in order to detect trends in sink efficiencies from the time course of fossil fuel-derived CO_2 emissions and temporal changes in land use, "it is necessary to disentangle the spin-up time and fossil fuel growth rate variation signatures in the airborne fraction from signatures due to other causes." When they make the pertinent calculations for fossil-fuel and land-use changes, they say they "do indeed find a positive trend in the residuals," but they argue this trend "is not statistically significant after correcting for known events such as the temporal distribution of the extrinsic forcings and likely omissions in the emissions (particularly from land-use change)," further noting their analysis suggests "trends in airborne fraction are not a very good diagnostic to detect changes in carbon sink efficiency because variations in the signal are complex and the signal-to-noise ratio is small."

Thus, Gloor *et al*. conclude "atmospheric data, if analyzed adequately, do not yet reveal a statistically significant signal." They further note, "although approximately one-half of total CO_2 emissions is at present taken up by combined land and ocean carbon reservoirs (Schimel *et al*., 2001)," coupled climate/carbon-cycle models "predict a decline in future carbon uptake by these reservoirs, resulting in a positive carbon-climate feedback."

In an effort to shed more light on the subject, Ballantyne *et al*. (2012) used "global-scale atmospheric CO_2 measurements, CO_2 emission inventories and their full range of uncertainties to calculate changes in global CO_2 sources and sinks during the past fifty years." The five U.S. scientists say their mass balance analysis shows "net global carbon uptake has increased significantly by about 0.05 billion tonnes of carbon per year and that global carbon uptake doubled, from 2.4 ± 0.8 to 5.0 ± 0.9 billion tonnes per year, between 1960 and 2010." Ballantyne *et al*. conclude, "although present predictions indicate diminished C uptake by the land and oceans in the coming century, with potentially serious consequences for the global climate, as of 2010 there is no empirical evidence that C uptake has started to diminish on the global scale."

Other research lends confidence to the idea that the carbon-sequestering strength of the land and ocean will continue in the future, even in the face of rising temperatures. Allen *et al*. (1999) analyzed sediment cores from a lake in Italy and the Mediterranean Sea, determining that over the past 102,000 years, the warm period of the Holocene produced organic carbon content in vegetation more than double that observed for any other period in this historic record. Similarly, Velichko *et al*. (1999) reconstructed carbon storage in vegetation in Northern Eurasia, determining plant life there was more productive and efficient in sequestering carbon at higher, as opposed to lower, air temperatures. Vegetative carbon storage during the Holocene Optimum, which occurred about 6,000 years ago, was calculated to be 120 percent greater than present-day carbon sequestration in this region.

In assessing the ability of Earth's vegetation to sequester carbon in the future, it is also important to consider the findings of Luz *et al*. (1999), who estimated the biospheric productivity of the planet as a whole is currently at its highest point in the past 82,000 years, as is the atmospheric CO_2 concentration. Xiao *et al*. (1998) used a process-based ecosystem model to compute global net ecosystem production from 1990 to 2100 based on three scenarios of atmospheric CO_2 and temperature change. In all cases where these parameters increased together, they reported positive increases in global net ecosystem productivity.

It should be clear from the observational data that Earth's biosphere is exerting a powerful brake on the rate of rise of the air's CO_2 content, such that the large increases in anthropogenic CO_2 emissions of the past two decades have not resulted in any increase in the rate of CO_2 accumulation in the atmosphere. The IPCC has yet to acknowledge the existence and sign of this negative feedback, choosing to rely on projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. Those models "consistently estimate a positive carbon cycle feedback, i.e. reduced natural sinks or increased natural CO_2 sources in response to future climate change." The models further find "in particular, carbon sinks in tropical land ecosystems are vulnerable to climate change" (p. 21 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

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2.6.2 Carbonyl Sulfide

Idso (1990) suggested the volatilization of reduced sulfur gases from Earth's soils may be just as important as dimethyl sulfide (DMS) emissions from the world's oceans in enhancing cloud albedo, cooling the planet, and providing a natural brake on the tendency for anthropogenically enhanced greenhouse gases to drive global warming. (See Dimethylsulfide, Section 2.6.2.1.1.)

Experiments have shown soil DMS emissions to be positively correlated with soil organic matter content, and Idso noted additions of organic matter to soils tend to increase the amount of sulfur gases they emit. Because atmospheric CO_2 enrichment augments plant growth and, as a result, vegetative inputs of organic matter to Earth's soils, Idso hypothesized this phenomenon should produce an impetus for cooling, even in the absence of the surface warming that sets in motion the chain of events that produce the oceanic DMS-induced negative feedback cooling the planet.

Two years later, Idso (1992) expanded his work to include another biologically produced sulfur gas emitted from soils: carbonyl sulfide, a chemical compound with the formula OCS, but often written as COS. He noted COS is likely to be emitted in increasing quantities as Earth's vegetation responds to the ongoing rise in the air's CO_2 content. While COS is relatively inert in the troposphere, it eventually makes its way into the stratosphere, where it is transformed into solar-radiation-reflecting sulfate aerosol particles. He concluded the CO_2-induced augmentation of soil COS emissions constitutes a mechanism that can cool the planet's surface in the absence of an impetus for warming, without producing additional clouds or making them any brighter.

Researchers subsequently have learned the COS-induced cooling mechanism also operates at sea, just as the DMS-induced cooling mechanism does, and it too possesses a warming-induced component in addition to its CO_2-induced component. Andreae and Ferek (1992) demonstrated ocean-surface COS concentrations are highly correlated with surface-water primary productivity. So strong is this correlation that Erickson and Eaton (1993) developed an empirical model for computing ocean-surface COS concentrations based solely on surface-water chlorophyll concentrations and values of incoming solar radiation.

Researchers also have learned an even greater portion of naturally produced COS is created in the atmosphere, where carbon disulfide and dimethyl sulfide—also largely of oceanic origin (Aydin *et al*., 2002)—undergo photochemical oxidation (Khalil and Rasmussen, 1984; Barnes *et al*., 1994). The majority of the tropospheric burden of COS is ultimately dependent upon photosynthetic activity occurring near the surface of the world's oceans.

The tropospheric COS concentration has risen by approximately 30 percent since the 1600s, from a mean value of 373 ppt over the period 1616–1694 to something on the order of 485 ppt today. Aydin *et al*. (2002) have noted only a quarter of this increase can be attributed to anthropogenic sources. The rest of the observed COS increase must have had a natural origin, a large portion of which must have been derived from the products and byproducts of marine photosynthetic activity, which must have increased substantially over the past three centuries. The increases in atmospheric CO_2 concentration and temperature experienced over this period were likely driving forces for the increase in tropospheric COS concentration and its subsequent transport to the stratosphere, where it could exert a cooling influence on the Earth. This chain of events may have kept the warming of the globe considerably below what it might otherwise have been.

Another aspect of this multifaceted global "biothermostat" was revealed in a laboratory study of samples of the lichen *Ramalina menziesii* collected from an open oak woodland in central California, USA by Kuhn and Kesselmeier (2000). When the lichens were optimally hydrated, the researchers found, they absorbed COS from the air at a rate that gradually doubled as air temperature rose from approximately 3° to 25°C, whereupon their rate of COS absorption began a precipitous decline that led to zero COS absorption at 35°C.

Most terrestrial plants thrive in temperatures much warmer than 3°C; as their surroundings warm and they grow better, they extract more COS from the atmosphere, promoting more warming and growing better still. But above a certain temperature warming becomes detrimental to plants, and they begin to reduce their rates of COS absorption, resulting in cooling. The carbonic anhydrase enzyme that governs the uptake of COS in lichens also controls it in all higher plants, algae, and soil organisms, suggesting this thermoregulatory function of the biosphere likely operates across the globe.

Sandoval-Soto *et al*. (2012) reiterated the importance of COS in the atmosphere, noting, "aside from sulfur dioxide, carbonyl sulfide (COS) is the most abundant sulfur gas in the atmosphere with relative constant mixing ratios of 450–500 ppt and a lifetime of more than two years." They point out "COS can be transported up into the stratosphere," where it "may serve as a source of sulfur to the stratospheric aerosol layer by conversion to sulfuric acid (Junge *et al*., 1961; Crutzen, 1976)," thereby contributing to the scattering of incoming solar radiation back to space and exerting a cooling influence on Earth. In addition, they note terrestrial vegetation "acts as the main sink for this trace gas," and it is "heavily underestimated" in this regard, citing the work of Notholt *et al*. (2003), Mu *et al*. (2004), Sandoval-Soto *et al*. (2005), Campbell *et al*. (2008), Suntharalingam *et al*. (2008), and Van Diest and Kesselmeier (2008).

Further exploring the relationship between increasing atmospheric CO_2 and COS, Sandoval-Soto *et al*. grew three- to four-year-old holm oak (*Quercus ilex* L.) and European beech (*Fagus sylvatica* L.) trees in greenhouse chambers from March 1998 to February 2000 at atmospheric CO_2 concentrations of either 350 or 800 ppm, measuring a number of plant physiological properties and processes. In the case of holm oak, the five researchers report there was "a decrease of the COS uptake capacity induced by high CO_2 levels under long-term conditions," and their data for beech support "a similar interpretation." They conclude increasing levels of atmospheric CO_2 may have had a tempering effect on Earth's rate of warming during the development of the planet's Current Warm Period, and that cooling influence could increase in the future.

This multifaceted phenomenon is clearly complex, with different biological entities affecting atmospheric COS concentrations simultaneously but in different ways, while periodically reversing directions in response to changing temperatures. There is obviously much to be learned about the plant physiological mechanisms that may be involved. Until the COS cycle is fully understood and incorporated into the climate models, it cannot be known just how much of the warming experienced during the twentieth century can be attributed to anthropogenic sources.

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2.6.3 Diffuse Light

Another negative feedback phenomenon is diffuse light. It operates through a chain of five linkages triggered by the incremental enhancement of the atmosphere's greenhouse effect produced by an increase in the air's CO_2 content.

The first linkage is the proven propensity for higher levels of atmospheric CO_2 to enhance vegetative productivity, a powerful negative feedback mechanism. Greater CO_2-enhanced photosynthetic rates, for example, enable plants to remove considerably more CO_2 from the air than they do under current conditions, while CO_2-induced increases in plant water use efficiency allow plants to grow where it was previously too dry for them. This establishes a potential for more CO_2 to be removed from the atmosphere by increasing the abundance of Earth's plants and increasing their robustness (see Carbon Sequestration, Section 2.6.1, this volume).

The second linkage of the feedback loop is the ability of plants to emit gases to the atmosphere that are ultimately converted into "biosols"—aerosols that owe their existence to the biological activities of Earth's vegetation, many of which function as cloud condensation nuclei. Since the existence of these atmospheric particles is dependent upon the physiological activities of plants and their associated soil biota, the CO_2-induced presence of more, and more-highly-productive, plants will lead to the production of more of these cloud-mediating particles, which can then result in more clouds that reflect sunlight and act to cool the planet.

The third linkage is the observed propensity for increases in aerosols and cloud particles to enhance the amount of diffuse solar radiation reaching Earth's surface. The fourth linkage is the ability of enhanced diffuse lighting to reduce the volume of shade within vegetative canopies. The fifth linkage is the tendency for less internal canopy shading to enhance whole-canopy photosynthesis, which produces the end result: a greater biological extraction of CO_2 from the air and the subsequent sequestration of its carbon.

Roderick *et al*. (2001) provide a good estimate of the significance of this process based on a unique "natural experiment," a technique used extensively by Idso (1998) to evaluate the climatic sensitivity of the planet. Roderick and his colleagues considered the volcanic eruption of Mt. Pinatubo in June 1991, which ejected enough gases and fine materials into the atmosphere to produce sufficient aerosol particles to greatly increase the diffuse component of the solar radiation reaching the surface of Earth from that point in time through much of 1993, while only slightly reducing the receipt of total solar radiation.

Based on a set of lengthy calculations, they conclude the Mt. Pinatubo eruption may have resulted in the removal of an extra 2.5 Gt of carbon from the atmosphere due to its diffuse-light-enhancing stimulation of terrestrial vegetation in the year following the eruption, which would have reduced the ongoing rise in the air's CO_2 concentration that year by about 1.2 ppm. The reduction they calculated is approximately the magnitude of the change in CO_2 concentration actually observed (Sarmiento, 1993).

Bolstering the attribution of this change to diffuse light, Roderick *et al*. note the CO_2 reduction was coincident with an El Niño event, whereas "previous and subsequent such events have been associated with increases in atmospheric CO_2." Moreover, the observed reduction in *total* solar radiation received at Earth's surface during this period would have had a tendency to reduce the amount of photosynthetically active radiation, would have had a tendency to cause the air's CO_2 content to rise by lessening global photosynthetic activity.

Further support for the new negative feedback phenomenon came in 2002, when a team of 33 researchers published the results of a comprehensive study (Law *et al*., 2002) that compared seasonal and annual values of CO_2 and water vapor exchange across sites in forests, grasslands, crops, and tundra—part of an international network called FLUXNET—investigating the responses of these exchanges to variations in a number of environmental factors, including direct and diffuse solar radiation. The researchers report "net carbon uptake (net ecosystem exchange, the net of photosynthesis and respiration) was greater under diffuse than under direct radiation conditions." In discussing this finding, which is the centerpiece of the negative feedback phenomenon described in this section, they note "cloud-cover results in a greater proportion of diffuse radiation and constitutes a higher fraction of light penetrating to lower depths of the canopy (Oechel and Lawrence, 1985)." They also report "Goulden *et al*. (1997), Fitzjarrald *et al*. (1995), and Sakai *et al*. (1996) showed that net carbon uptake was consistently higher during cloudy periods in a boreal coniferous forest than during sunny periods with the same PPFD [photosynthetic photon flux density]." They also write, "Hollinger *et al*. (1994) found that daily net CO_2 uptake was greater on cloudy days, even though total PPFD was 21–45 percent lower on cloudy days than on clear days."

Gu *et al*. (2003) "used two independent and direct methods to examine the photosynthetic response of a northern hardwood forest (Harvard Forest, 42.5°N, 72.2°W) to changes in diffuse radiation caused by Mount Pinatubo's volcanic aerosols." In the eruption year of 1991, they found, "around noontime in the mid-growing season, the gross photosynthetic rate under the perturbed cloudless solar radiation regime was 23, 8, and 4 percent higher than that under the normal cloudless solar radiation regime in 1992, 1993, and 1994, respectively," and "integrated over a day, the enhancement for canopy gross photosynthesis by the volcanic aerosols was 21 percent in 1992, 6 percent in 1993 and 3 percent in 1994." Gu *et al*. write, "because of substantial increases in diffuse radiation world-wide after the eruption and strong positive effects of diffuse radiation for a variety of vegetation types, it is likely that our findings at Harvard Forest represent a global phenomenon."

The diffuse-light-induced photosynthetic enhancement observed by Gu *et al*. was caused by volcanic aerosols acting under cloudless conditions. That distinguishes this phenomenon from a closely related one also described by Gu *et al*.—the propensity for the extra diffuse light created by increased cloud cover to enhance photosynthesis even though the total flux of solar radiation received at Earth's surface may be reduced under such conditions. Gu *et al*. note, "Harvard Forest photosynthesis also increases with cloud cover, with a peak at about 50 percent cloud cover."

The work reviewed above focuses on the enhanced atmospheric aerosol concentration caused by a singular significant event: a massive volcanic eruption. Niyogi *et al*. (2004) asked a more general question: "Can we detect the effect of relatively routine aerosol variability on field measurements of CO_2 fluxes, and if so, how does the variability in aerosol loading affect CO_2 fluxes over different landscapes?"

The group of 16 researchers used CO_2 flux data from the AmeriFlux network (Baldocchi *et al*., 2001) together with cloud-free aerosol optical depth data from the NASA Robotic Network (AERONET; Holben *et al*., 2001) to assess the effect of aerosol loading on the net assimilation of CO_2 by three types of vegetation: trees (broadleaf deciduous forest and mixed forest), crops (winter wheat, soybeans, and corn), and grasslands.

Their work revealed an aerosol-induced increase in diffuse radiative-flux fraction [DRF = ratio of diffuse (Rd) to total or global (Rg) solar irradiance] increased the net CO_2 assimilation of trees and crops, making them larger carbon sinks, but decreased the net CO_2 assimilation of grasslands, making them smaller carbon sinks. For a summer midrange Rg flux of 500 W m^{-2}, going from the set of all DRF values between 0.0 and 0.4 to the set of all DRF values between 0.6 and 1.0 resulted in an approximate 50 percent increase in net CO_2 assimilation by a broadleaf deciduous forest located in Tennessee, USA. Averaged over the entire daylight period, the shift from the lower to the higher set of DRF values "enhances photosynthetic fluxes by about 30 percent at this study site." Similar results were obtained for the mixed forest and the conglomerate of crops studied. Niyogi *et al*. conclude natural variability among commonly present aerosols can "routinely influence surface irradiance and hence the terrestrial CO_2 flux and regional carbon cycle." For these types of land cover (forests and agricultural crops), that influence significantly increases the assimilation of CO_2 from the atmosphere. In the case of grasslands, Niyogi *et al*. found the opposite effect, with greater aerosol loading of the atmosphere leading to less CO_2 assimilation. The researchers suggest this result was most likely due to grasslands' significantly different canopy architecture.

With respect to the planet as a whole, the net effect of diffuse light processes is decidedly positive, as Earth's trees are key in carbon sequestration. Post *et al*. (1990) note woody plants account for approximately 75 percent of terrestrial photosynthesis, which represents about 90 percent of all photosynthesis (Sellers and McCarthy, 1990).

Moreover, much of the commonly present aerosol burden of the atmosphere is plant-derived. Woody plants are themselves responsible for emitting to the air that which ultimately enhances photosynthesis. Earth's trees alter the atmospheric environment in a way that directly enhances their growth. And as humans release more CO_2 into the atmosphere, the globe's woody plants respond to its aerial fertilization effect, becoming increasingly productive, leading to even more plant-derived aerosols being released to the atmosphere, further stimulating this positive feedback cycle. These effects are not adequately incorporated into the climate models.

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2.6.4 Iodocompounds

The climatic significance of iodinated compounds, or iodocompounds, was initially described in *Nature* by O'Dowd *et al*. (2002). As related by Kolb (2002) in an accompanying perspective on their work, the 10-member research team discovered "a previously unrecognized source of aerosol particles" by unraveling "a photochemical phenomenon that occurs in sea air and produces aerosol particles composed largely of iodine oxides."

O'Dowd *et al*. used a smog chamber operated under coastal atmospheric conditions to demonstrate, as they report, "new particles can form from condensable iodine-containing vapors, which are the photolysis products of biogenic iodocarbons emitted from marine algae." They also demonstrated, using aerosol formation models, that concentrations of condensable iodine-containing vapors over the open ocean "are sufficient to influence marine particle formation."

The aerosol particles O'Dowd *et al.* discovered can function as cloud condensation nuclei (CCN), helping to create new clouds that reflect more incoming solar radiation back to space and thereby cool the planet (a negative feedback). With respect to the negative feedback nature of this phenomenon, O'Dowd *et al.* cite the work of Laturnus *et al*. (2000), who demonstrated emissions of iodocarbons from marine biota "can increase by up to 5 times as a result of changes in environmental conditions associated with global change." Therefore, O'Dowd *et al*. write, "increasing the source rate of condensable iodine vapors will result in an increase in marine aerosol and CCN concentrations of the order of 20–60 percent." Furthermore, they note, "changes in cloud albedo resulting from changes in CCN concentrations of this magnitude can lead to an increase in global radiative forcing similar in magnitude, but opposite in sign, to the forcing induced by greenhouse gases."

Four years later, Smythe-Wright *et al*. (2006) measured trace gas and pigment concentrations in seawater, while identifying and enumerating picophytoprokaryotes during two ship cruises in the Atlantic Ocean and one in the Indian Ocean, where they focused "on methyl iodide production and the importance of a biologically related source." They encountered methyl iodide concentrations as great as 45 pmol per liter in the top 150 meters of the oceanic water column that correlated well with the abundance of *Prochlorococcus*, which they reported "can account for >80 percent of the variability in the methyl iodide concentrations." They further state they "have confirmed the release of methyl iodide by this species in laboratory culture experiments."

Extrapolating their findings to the globe as a whole, the six researchers "estimate the global ocean flux of iodine [I] to the marine boundary layer from this single source to be 5.3×10^{11} g I year^{-1}," which they state "is a large fraction of the total estimated global flux of iodine (10^{11}-10^{12} g I year^{-1})." Smythe-Wright *et al*. point out volatile iodinated compounds "play a part in the formation of new particles and cloud condensation nuclei (CCN)," and "an increase in the production of iodocompounds and the subsequent production of CCN would potentially result in a net cooling of the Earth system and hence in a negative climate feedback mechanism, mitigating global warming." They suggest "as ocean waters become warmer and more stratified, nutrient concentrations will fall and there will likely be a regime shift away from microalgae toward *Prochlorococcus*," such that "colonization within the <50° latitude band will result in a ~15 percent increase in the release of iodine to the atmosphere," with consequent "important implications for global climate change."

As part of the Third Pelagic Ecosystem CO_2 Enrichment Study, Wingenter *et al*. (2007) investigated the effects of atmospheric CO_2 enrichment on marine microorganisms in nine marine mesocosms maintained within two-meter-diameter polyethylene bags submerged to a depth of 10 meters in a fjord at the Large-Scale Facilities of the Biological Station of the University of Bergen in Espegrend, Norway. Three of these mesocosms were maintained at ambient levels of CO_2 (~375 ppm or base CO_2), three were maintained at levels expected to prevail at the end of the current century (760 ppm or $2xCO_2$), and three were maintained at levels predicted for the middle of the next century (1150 ppm or $3xCO_2$). During the 25 days of this experiment, the researchers followed the development and subsequent decline of an induced bloom of the coccolithophorid *Emiliania huxleyi*, carefully measuring several physical, chemical, and biological parameters along the way. This work revealed iodo-carbon chloroiodomethane (CH_2CII) concentrations peaked about six to 10 days after the coccolithophorid's chlorophyll-a maximum, and the peak estimated abundance was 46 percent higher in the $2xCO_2$ mesocosms and 131 percent higher in the $3xCO_2$ mesocosms.

The international team of scientists concludes the differences in the CH_2CII concentrations "may be viewed as a result of changes to the ecosystems as a whole brought on by the CO_2 perturbations." Because emissions of various iodocarbons have been found to lead to an enhancement of cloud condensation nuclei in the marine atmosphere, as demonstrated by O'Dowd *et al*. (2002) and Jimenez *et al*. (2003), the CO_2-induced stimulation of marine emissions of these substances provides a natural brake on the tendency for global warming to occur as a consequence of any forcing, as iodocarbons lead to the creation of more highly reflective clouds over greater areas of the world's oceans. As Wingenter *et al*. conclude, the processes described above "may help contribute to the homeostasis of the planet."

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2.6.5 Stratospheric Perturbations

Few researchers have examined the influence of the stratosphere on global climate, yet several studies indicate this layer of the atmosphere has a significant impact on various climate parameters.

In an early study of the subject, Hartley *et al*. (1998) utilized meteorological data for the winter of 1992–93 to study a broad range of stratospheric polar vortex distortions for possible impacts on meteorological events in the troposphere. As they describe it, the results of their study "clearly indicate that stratospheric processes induce significant anomalies in dynamical fields at the tropopause."

Previously, although atmospheric processes of tropospheric origin were known to have the ability to perturb the stratosphere, feedback in the opposite direction was assumed to be negligible. The results of Hartley *et al.*'s study, however, demonstrate this assumption was incorrect, leading them to suggest a more realistic representation of the stratosphere may be required to enable general circulation models (GCMs) of the atmosphere to properly simulate the troposphere.

This shortcoming of current climate models may be critical, for scientists have long suspected the upper atmosphere may amplify the effects of a number of solar phenomena. The work of Hartley *et al*. suggests the amplified perturbations of these phenomena may be propagated downward to the troposphere, where they could significantly impact Earth's climate.

Initial evidence that such perturbations may indeed influencing climate near Earth's surface is seen in the work of Thompson and Solomon (2002), who explored a number of different data sets in Antarctica to define the nature of climate change in Antarctica since 1969 and determine the reasons for the observed changes. The two researchers found "at the surface, the Antarctic Peninsula has warmed by several [degrees C] over the past several decades, while the interior of the Antarctic continent has exhibited weak cooling." In addition, they note, "ice shelves have retreated over the peninsula and sea-ice extent has decreased over the Bellingshausen Sea, while sea-ice concentration has increased and the length of the sea-ice season has increased over much of eastern Antarctica and the Ross Sea." With respect to atmospheric circulation, they write there was "a systematic bias toward the high-index polarity of the SAM," or Southern Hemispheric Annular Mode, such that the ring of westerly winds encircling Antarctica recently has been spending more time in its strong-wind phase.

The heightened strength and persistence of the SAM can explain most of the cooling experienced over the bulk of Antarctica over the past several decades as well as much of the warming of the Antarctica Peninsula, as the latter location experiences fewer cold-air outbreaks under such conditions while simultaneously receiving increased advective warmth from the Southern Ocean. As for what caused the strengthening of the SAM, Thompson and Solomon speculate it is related to "recent trends in the lower stratospheric polar vortex, which are due largely to photochemical ozone losses."

Similar findings were reported in a contemporaneous study conducted by Kwok and Comiso (2002), who also report the SAM index shifted towards more positive values (0.22/decade) over the 17-year period 1982–1998, while noting a positive polarity of the SAM index "is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau." Simultaneously, the SO index shifted in a negative direction, indicating "a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over much of the continent." The authors report the positive trend in the coupled mode of variability of these two indices (0.3/decade) represents a "significant bias toward positive polarity," which they describe as "remarkable."

Kwok and Comiso note "the tropospheric SH annular mode has been shown to be related to changes in the lower stratosphere (Thompson and Wallace, 2000)" and "the high index polarity of the SH annular mode is associated with the trend toward a cooling and strengthening of the SH stratospheric polar vortex during the stratosphere's relatively short active season in November, and ozone depletion," much the same theory put forth by Thompson and Solomon (2002).

Thejll *et al*. (2003) also demonstrated a link between stratospheric perturbations and tropospheric climate. They investigated various spatial and temporal relationships among several parameters, including the geomagnetic index (*Ap*), the NAO, stratospheric geopotential height, and sea level pressure. The three researchers report "significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000," but "for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere." By using "Monte Carlo simulations of the statistical procedures applied to suitable surrogate data," they conclude these correlations are due to the existence of a "real physical link." They also note in the 1973–2000 period only the winter season series are significantly correlated, which they said "is consistent with the notion that the solar-climate link works through the stratosphere."

Thejll *et al*. suggest their findings may be explained in two different ways: either the influence of the Sun increased through time, reaching a strong enough level in the 1970s to make the correlations they studied become statistically significant, or the state of the atmosphere changed in the 1970s, becoming more sensitive to the solar influence than it had been. In either event, their findings strengthen the argument for solar-induced perturbations being propagated downward from the stratosphere to the troposphere (Hartley *et al*., 1998; Carslaw *et al*., 2002).

Ineson *et al.* (2011) modeled the effects from realistic solar UV (200–320 nm) irradiance changes between solar activity minima and maxima in the stratosphere and mesosphere, finding weaker westerly winds during the winters with a less active Sun that may correspond with cold winters in Northern Europe and the United States and mild winters over Southern Europe and Canada, as observed in recent years. The observational analyses by Hood *et al.* (2013) added insight into the specific regional patterns of near-surface responses that more than likely originate from the solar UV forcing of ozone and related wind-thermal fields in the stratosphere.

Kristjansson *et al*.'s (2002) observation that "low clouds appear to be significantly inversely correlated with solar irradiance" led them to suggest a possible physical mechanism linked to the stratosphere that could explain this phenomenon. This mechanism, in their words, "acts through UV [ultraviolet radiation] in the stratosphere affecting tropospheric planetary waves and hence the subtropical highs, modulated by an interaction between sea surface temperature [SST] and lower tropospheric static stability," which "relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics." Based on experimentally determined values of factors that enter into this process, they obtained a value for the amplitude of the variation in low cloud cover over a solar cycle that "is very close to the observed amplitude."

Tiwari *et al*. (2005) report the Asian SouthWest Monsoon (SWM) intensity on a centennial scale "is governed by variation in TSI," yet "variations in TSI (~0.2%) seem to be too small to perturb the SWM, unless assisted by some internal amplification mechanism with positive feedback." They discuss a possible mechanism that "involves heating of the Earth's stratosphere by increased absorption of solar ultraviolet (UV) radiation by ozone during periods of enhanced solar activity (Schneider, 2005)." They posit more UV reception leads to more ozone production in the stratosphere, which leads to more heat being transferred to the troposphere, which leads to enhanced evaporation from the oceans, which enhances monsoon winds and precipitation.

de Jager (2005) reviewed what is known about the role of the Sun in orchestrating climate change over the course of the Holocene, including changes that occurred during the twentieth century. Commenting on the direct effects of solar irradiance variations, de Jager reports "the fraction of the solar irradiance that directly reaches the Earth's troposphere is emitted by the solar photosphere [and] does not significantly vary." The variable part of this energy flux, he states, is emitted by chromospheric parts of centers of solar activity, and "it only directly influences the higher, stratospheric terrestrial layers," which "can only influence the troposphere by some form of stratosphere-troposphere coupling."

Solomon *et al*. (2010) point out "the trend in global surface temperatures has been nearly flat since the late 1990s despite continuing increases in the forcing due to the sum of the well-mixed greenhouse gases (CO_2, CH_4, halocarbons, and N_2O), raising questions regarding the understanding of forced climate change, its drivers, the parameters that define natural internal variability, and how fully these terms are represented in climate models." They used observations of stratospheric water vapor concentration obtained over the period 1980–2008, together with detailed radiative transfer and modeling information, to calculate the global climatic impact of water vapor and compare it with trends in mean global near-surface air temperature observed over the same time period.

The seven scientists found stratospheric water vapor concentrations decreased by about 10 percent after the year 2000, and their analysis indicates this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25 percent compared to what would have been expected on the basis of climate model calculations due to measured increases in carbon dioxide and other greenhouse gases over the same period. In addition, they found, "more limited data suggest that stratospheric water vapor probably increased between 1980 and 2000, which would have enhanced the decadal rate of surface warming during the 1990s by about 30% [above what it would have been without the stratospheric water vapor increase]."

Solomon *et al*. conclude it is "not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability." In either case, their findings describe a phenomenon not included in prior analyses of global climate change. They also indicate current climate models do not "completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures, or the impact of aerosol heating on water input to the stratosphere."

In light of Solomon *et al*.'s findings, their identification of what current climate models do not but should do, and the questions they say are raised by the flatlining of mean global near-surface air temperature since the late 1990s, it is premature to conclude current state-of-the-art models know enough to correctly simulate the intricate workings of Earth's climate regulatory system. The other studies cited in this section also indicate much research remains to be conducted in order to more correctly characterize and quantify the stratosphere's influence on global climate.

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2.6.6 Volcanism

Volcanic forcings are not a function of human activities. Their impact on climate and human history is well documented and takes many forms, especially with major events with a global impact such as Tambora, Laki, and more recently Pinatubo.

In general, large volcanic eruptions eject particulate and aerosol materials into the stratosphere. These aerosols, primarily sulfate type, increase the albedo of the planet, which means less solar radiation coming in. The result is a cooling of the lower troposphere and surface. Generally, the greater the eruption, the stronger this effect will be and the longer it will last. Smaller volcanic eruptions confined to the troposphere have little effect on the climate, as the troposphere is more efficient in scavenging out the relatively large particulates. Still, much remains to be learned about this external forcing of the climate, and as the research highlighted below indicates, not all scientists are in agreement regarding the long-term importance of this forcing on climate.

Briffa and Jones (1998) used tree-ring wood density data from more than 380 boreal forest locations in the Northern Hemisphere as surrogates for summertime temperatures, looking for effects of large volcanic eruptions on climate since 1400 AD. This exercise indicated major volcanic eruptions seemed to produce significant Northern Hemispheric cooling the year after their occurrence, with the largest of the temperature declines they detected estimated to be 0.81°C in 1601, the year following the eruption of Huaynaputina in Peru.

Of the six centuries examined, the seventeenth century experienced the greatest number (six) of climatically significant eruptions. Strong temperature anomalies suggested there were three other major volcanic eruptions during the late seventeenth century not reported in historical accounts. The researchers also found every Northern Hemispheric temperature departure of 0.3°C or more since 1400 (19 total events) followed a confirmed major volcanic eruption. This study thus suggests there is a strong link between volcanic activity and large-scale temperature variability, and it may help to explain the cool temperatures of the Little Ice Age by illustrating how closely spaced multiple eruptions could reduce hemispheric temperatures on decadal and multidecadal time scales, as well as how a lack of such eruptions could result in periods of warmer global temperatures.

Building on this perceived relationship, Hyde and Crowley (2000) analyzed statistical properties of climatically significant volcanic eruptions over the past 600 years in an effort to estimate the probability of future eruptions. They conclude there was a 35 to 40 percent probability of a volcanic eruption occurring with the capability of producing a radiative perturbation of -1 W m^{-2} or larger in the following 10 years. Such an eruption was estimated to produce a

0.1°C to 0.15°C cooling over a two- to three-year period, while the probability of a larger Mt. Pinatubo-scale eruption with a radiative perturbation of -3 W m^{-2} was estimated to be 15 to 25 percent. The two scientists note if a major volcanic eruption were to occur in the next decade (which seems a reasonable possibility), it could "mask the CO_2 effect and complicate discussions on a greenhouse gas protocol."

Sadler and Grattan (1999) examined a number of issues related to the linking of volcanic activity with spatial and temporal events in climatic, historical, and palaeoecological records. Although volcanoes can have a significant effect on proximal climates, they conclude, their global impact is less well understood. The message of their paper is thus one of caution in drawing conclusions about climate change and its connection to volcanic explosions. They report, for example, "a run of bad summers, an increase in sea ice off America, narrow rings in dendrochronological sequences, and neoglaciations can all be linked to temporally convenient climate forcing by volcanic aerosols." In addition, they note "speculation as to the likely effect of these eruptions on fauna and flora and human societies may involve further supposition." They also note "the role of precursor climatic and/or environmental conditions is frequently overlooked" and "it is valid to question whether the relationships established are fortuitous rather than dependent." As one of the scientists they quote has aptly phrased it, "an eruption here, a destruction there, a plague somewhere else—all are too easily linked in hasty surmise."

Yet another indication the climatic effects of volcanic eruptions may not be well established is provided by Douglass and Knox (2005), who "determined the volcano climate sensitivity and response time for the Mount Pinatubo eruption, using observational measurements of the temperature anomalies of the lower troposphere, measurements of the long wave outgoing radiation, and the aerosol optical density." Their analysis revealed "a short atmospheric response time, of the order of several months, leaving no volcano effect in the pipeline, and a negative feedback to its forcing."

One of the issues raised by these results, according to Douglass and Knox, concerns "the origin of the required negative feedback." With respect to this question, they report "negative feedback processes have been proposed involving cirrus clouds (Lindzen *et al*., 2001)" and "Sassen (1992) reports that cirrus clouds were produced during the Mt. Pinatubo event." In addition, they note the adaptive infrared iris concept of Lindzen *et al*. (2001) "yields a negative feedback factor of -1.1, which is well within the error estimate of the feedback found by us." They also observe the short intrinsic response time they derived (6.8 ± 1.5 months) "confirms suggestions of Lindzen and Giannitsis (1998, 2002) that a low sensitivity and small lifetime are more appropriate" than the "long response times and positive feedback" characteristic of the reigning climate paradigm.

Tuffen (2010) writes "there is growing evidence that past changes in the thickness of ice covering volcanoes have affected their eruptive activity." He further states "the rate of volcanic activity in Iceland accelerated by a factor of 30–50 following the last deglaciation at approximately 12 ka (Maclennan *et al*., 2002)" and "analyses of local and global eruption databases have identified a statistically significant correlation between periods of climatic warming associated with recession of ice and an increase in the frequency of eruptions (Jellinek *et al*., 2004; Nowell *et al*., 2006; Huybers and Langmuir, 2009)." Thus he asks the next logical question: "Will the current ice recession provoke increased volcanic activity and lead to increased exposure to volcanic hazards?"

Tuffen—a researcher at the Lancaster Environment Centre of Lancaster University in the United Kingdom—"analyze[d] our current knowledge of how ice thickness variations influence volcanism" and "identif[ied] several unresolved issues that currently prevent quantitative assessment of whether activity is likely to accelerate in the coming century." He found "ice unloading may encourage more explosive eruptions" but "melting of ice and snow may decrease the likelihood and magnitude of meltwater floods." On the other hand, he writes, there is "uncertainty about the time scale of volcanic responses to ice unloading," "poor constraint on how ice bodies on volcanoes will respond to twenty-first century climate change," and "lack of data on how past changes in ice thickness have affected the style of volcanic eruptions and associated hazards." He also notes "the sensitivity of volcanoes to small changes in ice thickness or to recession of small glaciers on their flanks is unknown," "it is not known how localized ice withdrawal from stratovolcanoes [tall, conical volcanoes with many layers (strata) of hardened lava, tephra, and volcanic ash] will affect shallow crustal magma storage and eruption," and "broader feedbacks between volcanism and climate change remain poorly understood."

The U.K. researcher concludes by stating, "in order to resolve these problems, both new data and improved models are required." With respect to data, he adds, "existing databases of known volcanic eruptions need to be augmented by numerous detailed case studies of the Quaternary eruptive history of ice-covered volcanoes." Regarding models, he notes, "improved physical models are required to test how magma generation, storage and eruption at stratovolcanoes are affected by stress perturbations related to the waxing and waning of small-volume ice bodies on what is commonly steep topography." Finally, he states, "feedbacks between the mass balance of ice sheets and glaciers and volcanic activity need to be incorporated into future Earth-system models."

Kravitz *et al*. (2011) focused on the ability of climate models to correctly represent volcanic aerosol forcing of climate. In June 2009, the Sarychev volcano in the Kamchatka Peninsula erupted explosively for a period of approximately five days. It injected 1.2 terragrams (Tg) of material into the atmosphere to an estimated height of as much as 16 km, nearly 10 miles It was the second such eruption within a year. Taking advantage of this opportunity, Kravitz *et al*. studied measurements of the optical depth of the aerosol sulfates from the eruption and compared them with the projected output from a 20-member GCM ensemble, aiming to provide suggestions for improving the model's capabilities. They used the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies Model-E, a coupled atmosphere-ocean GCM with fairly coarse resolution in the horizontal (4° by 5° lat/lon) and vertical (23 layers). The model contained levels up to 80 km, necessarily including the stratosphere.

The control model run consisted of a 20-member suite globally over the period 2007–2010. In this experiment, 1.5 Tg of volcanic material was injected into the atmosphere at a point near Sarychev in 2008 of the model year. The observed aerosol measurements came from ground-based LIDARS at six locations around the world as well as satellite-based measurements that profile the aerosol concentration using scattered sunlight (Optical Spectrograph and Infrared Imaging System (OSIRIS)).

The model did a reasonably good job spreading the volcanic material around the Northern Hemisphere, but there were some important discrepancies between the model and observations (see Figure 2.6.6.1). The model transported the material too quickly into the tropics and too slowly into the high latitudes. The authors speculate this error may highlight the need to improve the model's stratospheric circulation. The model also tended to remove aerosols too quickly from the atmosphere, especially in the high latitudes, which may have been a function of the model overestimating particulate size. As shown in Figure 2.6.6.1, the modeled peak aerosol values occur one month earlier than observed and then decrease in concentration too quickly. The work of Kravitz *et al*. highlights the difficulty of developing climate models that accurately represent the influence of volcanic-induced aerosols on climate, where the likely impact on surface temperature from the Kravitz *et al*. experiment would be a bias toward warm temperatures on the time scale of months.

Clearly there remain significant uncertainties and disagreements about the climatic effects of volcanic eruptions, showing a need for further research into this topic.

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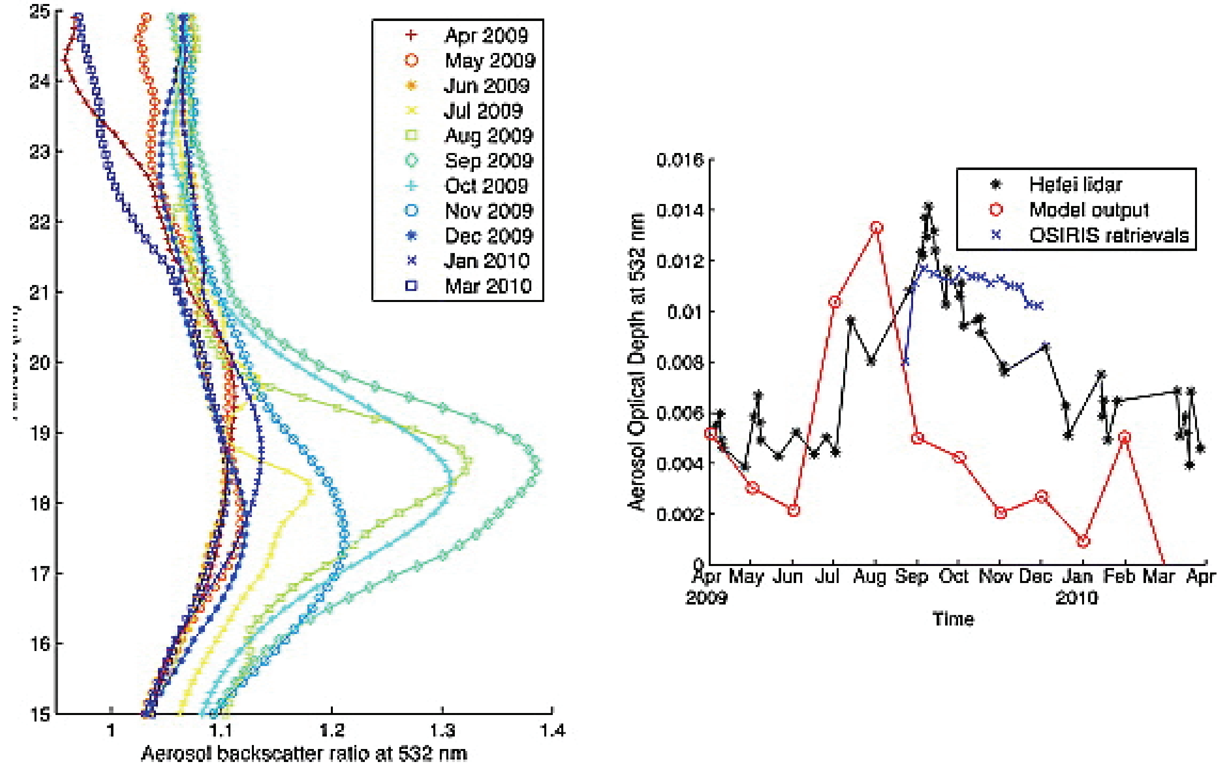

Figure 2.6.6.1. The LIDAR retrievals from Hefei, China as compared to model output and OSIRIS retrievals. (left) The monthly averages of backscatter as a function of altitude maximizing in September 2009. (right) The integrated (15-25 km) optical depth through the stratosphere for the LIDAR data (black), zonally averaged stratospheric aerosol optical depth calculated by the model in the grid latitude containing the Hefei LIDAR (28°-32°N) (red), and OSIRIS retrievals zonally averaged over the latitude band 30°-35°N (blue). Reprinted with permission from Kravitz, B., Robock, A., Bourassa, A., Deshler, T., Wu, D., Mattis, I., Finger, F., Hoffmann, A., Ritter, C., Bitar, L., Duck, T.J., and Barnes, J.E. 2011. Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. *Journal of Geophysical Research—Atmospheres* **116**: D18211, doi:10.1029/ 2010JD015501, Figure 11.

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3

Solar Forcing of Climate

Willie Soon (USA)

Sebastian Lüning (Germany)

Key Findings

Introduction

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Key Findings

The following points summarize the main findings of this chapter:

- Evidence is accruing that changes in Earth's surface temperature are largely driven by variations in solar activity. Examples of solar-controlled climate change epochs include the Medieval Warm Period, Little Ice Age and Early Twentieth Century (1910–1940) Warm Period.

- The Sun may have contributed as much as 66% of the observed twentieth century warming, and perhaps more.

- Strong empirical correlations have been reported from all around the world between solar variability and climate indices including temperature, precipitation, droughts, floods, streamflow, and monsoons.

- IPCC models do not incorporate important solar factors such as fluctuations in magnetic intensity and overestimate the role of human-related CO_2 forcing.

- The IPCC fails to consider the importance of the demonstrated empirical relationship between solar activity, the ingress of galactic cosmic rays, and the formation of low clouds.

- The respective importance of the Sun and CO_2 in forcing Earth climate remains unresolved; current climate models fail to account for a plethora of known Sun-climate connections.

- The recently quiet Sun and extrapolation of solar cycle patterns into the future suggest a planetary cooling may occur over the next few decades.

Introduction

The 2007 *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) claims "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations [italics in the original]" (IPCC, 2007-I, p. 10). The authors go so far as to suggest there is a better-than-90-percent probability their assessment is true. Similar assertions are made in the IPCC's forthcoming *Fifth Assessment Report* (AR5), which concludes "CO_2 is the strongest driver of climate change compared to other changes in the atmospheric composition, and changes in surface conditions. Its relative contribution has further increased since the 1980s and by far outweighs the contributions from natural drivers" (p. 7 of the Summary for Policy Makers, Second Order Draft of AR5, dated October 5, 2012). But as demonstrated in Chapter 1 of this report, the global climate models upon which the IPCC rests its case are notoriously unreliable.

Chapter 2 documented feedback factors and forcings the IPCC has downplayed or overlooked, and Chapters 4–7 will show that real-world climate observations do not confirm the trends the IPCC claims should exist if its theory of CO_2-dominated climate change were true. This chapter explores an alternative theory of climate change the IPCC has rejected: that the *Sun's* influence likely played the more dominant role in Earth's climate over the past century and beyond.

The following statements taken from the Second Order Draft (SOD) of AR5 illustrate the IPCC's rejection of the Sun's influence as a major factor in contemporary climate change:

> Changes in the astronomical alignment of the Sun and Earth induce cyclical changes in radiative forcing, but this is substantial only at millennial and longer timescales. (p. 8.30, SOD)
>
> Quantification of the contributions of anthropogenic and natural forcing using multi-signal detection and attribution analyses show it is extremely likely that human activities (with very high confidence) have caused most (at least 50%) of the observed increase in global average temperatures since 1951. Detection and attribution analyses show that the greenhouse gas warming contribution of 0.6°C–1.4°C was very likely greater than the observed warming of 0.6°C over the period 1951–2010. The response to aerosols and other anthropogenic forcings appears to be less clearly detectable using CMIP5 models than it was using CMIP3 models, but they probably contributed a net cooling over this period (Figure TS.8). Such analyses also indicate a trend of less than 0.1°C was attributable to combined forcing from solar irradiance variations and volcanic eruptions over this period. Taken together with other evidence this indicates that it is extremely unlikely that the contribution from solar forcing to the warming since 1950 was larger than that from greenhouse gases. Better understanding of pre-instrumental data shows that observed warming over this period is far outside the range of internal climate variability estimated from such records, and it is also far outside the range of variability simulated in climate models. Based on the surface temperature record, we therefore assess that it is virtually certain that warming since 1950 cannot be explained by internal variability alone. (p.23 of the Technical Summary, SOD)

Much of the IPCC's examination of the possible influence of the Sun on Earth's climate begins and ends with a discussion of total solar irradiance (TSI). According to the IPCC, secular trends in TSI are too small—estimated at only +0.04 [-0.01 to +0.09] W m^{-2} since 1750—to have had much of an influence on the rising temperatures of the Current Warm Period. But as the material in this chapter shows, the IPCC is likely vastly underestimating this influence.

One possible reason, according to Soon *et al.* (2011), may rest in the fact that the low-amplitude TSI reconstruction estimates utilized by the IPCC and others (e.g., Lean *et al*., 2005) are based on computer modeling by Wang *et al.* (2005), whose magnetic flux transport model "was not designed to model irradiance changes or to assess the solar energy budget." In addition, Soon *et al*. note Wang *et al.*'s model "does not even contain a radiative transfer routine, which is essential to a proper description of solar physics" leaving Soon *et al.* to conclude "the Lean *et al*. (2005) reconstruction [used by the IPCC] is limited in its ability to describe variations in TSI." Additional discussion of the reconstruction of the TSI history can be found in pp. 46–47 of Soon and Legates (2013).

A second reason the IPCC fails to acknowledge a significant solar influence on recent climate is that it is looking for evidence (or rather a lack thereof) in the wrong places. Determining the correct or proper climatic metric to discern a solar-climate link may not be not as straightforward as it would seem. From Lindzen (1994) to Karamperidou *et al.* (2012), for example, it has been proposed that perhaps the most relevant variable for studying how climate varies is the so-called Equator-to-Pole temperature gradient (EPTG) (traditionally, the Northern Hemisphere record is considered because the data coverage over the Southern Hemisphere is sparse and less reliable), not near-surface air temperatures, which Lindzen (1994) interpreted to be simply a residual product of the change in EPTG rather than the other way around.

Figure 3.1 illustrates the value of plotting TSI values with the Northern Hemisphere EPTG data. As indicated in the left panel of the figure, the close

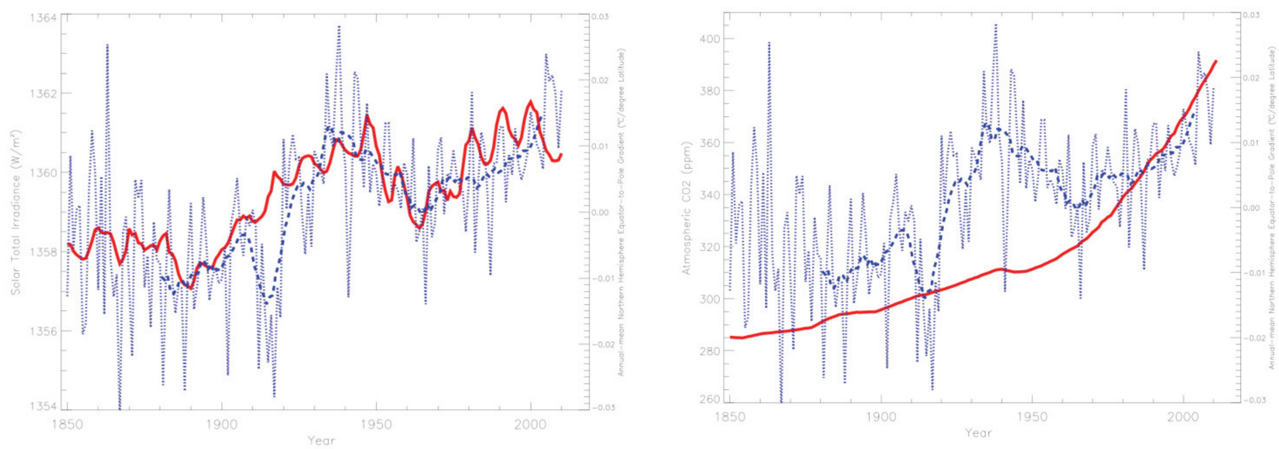

Figure 3.1. A comparison and contrast of the modulation of the Northern-Hemispheric equator-to-pole temperature gradient (both panels, dotted blue curves) by Total Solar Irradiance (TSI, left panel, solid red line) and by atmospheric CO_2 (right panel, solid red line). Adapted from Soon, W. and Legates, D.R. 2013. Solar irradiance modulation of Equator-to-Pole (Arctic) temperature gradients: Empirical evidence for climate variation on multi-decadal timescales. *Journal of Atmospheric and Solar-Terrestrial Physics* **93**: 45–56.

correlation between the data demonstrates the Sun's role in climate should not be discounted or outright dismissed, illustrating the potentially dominant role of the TSI in modulating climate on timescales of multiple decades to a century. A much weaker correlation is seen in the right panel of the figure, which displays atmospheric CO_2 data in the place of TSI, suggesting a much more tenuous and implausible relationship between atmospheric CO_2 and climate.

Throughout this chapter we examine evidence for an alternative theory of climate change: That variations in the Sun's radiation output and magnetic field, mediated by cosmic ray fluxes and changes in global cloud cover, play a larger role in regulating Earth's temperature, precipitation, droughts, floods, monsoons, and other climate features than any past or expected human activities, including projected increases in greenhouse gas (GHG) emissions. We also discuss another mechanism involving the ultraviolet (UV) component of solar radiation, which fluctuates much more intensely than the visible light. The UV changes are known to cause significant changes in the stratosphere, affecting ozone, and recent studies suggest these effects may propagate down into the lower atmosphere through complex physical and chemical interactions.

We begin by analzing research on solar irradiance, followed by an in-depth discussion of the cosmic ray theory of climate forcing. We then review empirical evidence linking solar variability to climate phenomena in both ancient and modern times. Establishing this latter fact is important because regardless of the mechanism(s) involved, the fact that such tightly coupled relationships exist in nature supports the thesis that relatively small fluctuations in solar output can indeed produce significant changes in climate.

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3.1 Solar Irradiance

Changes in solar irradiance and ultraviolet radiation may yield a much larger influence on global climate than that envisioned by the IPCC to result from rising atmospheric CO_2 (see, for example, Soon *et al.* 2000). The often-used comparison of the *relative* radiative forcing of the Sun's irradiance versus rising atmospheric CO_2, as popularized in the IPCC reports, misses important physical insights.

In evaluating the overall significance of solar vs. CO_2 forcings, an apples-to-apples comparison would be to contrast the role of these two parameters on an *absolute* scale. For incoming solar radiation, the absolute forcing amounts to around 340 W m^{-2} at the top of the atmosphere. The absolute forcing of atmospheric CO_2 is estimated at about 32-34 W m^{-2} (see pp. 202–203 of Kiehl and Trenberth 1997). (A recent publication by Huang [2013, p. 1707], however, has calculated this value may be as high as 44.1 W m^{-2}.) Small changes in the absolute forcing of the Sun can easily result in values much larger than the predicted changes in radiative forcing typically associated with increasing CO_2, and these forcings could easily influence Earth's climate.

Evidence for a much stronger relationship between the Sun and Earth's climate than that envisioned by the IPCC is seen in many empirical studies. Karlén (1998), for example, examined proxy climate data related to changes in summer temperatures in Scandinavia over the past 10,000 years. This temperature record—derived from analyses of changes in the size of glaciers, changes in the altitude of the alpine tree-limit, and variations in the width of annual tree rings—was compared with contemporaneous solar irradiance data derived from ^{14}C anomalies measured in tree rings. The record revealed both long- and short-term temperature fluctuations found to be "closely related" to the ^{14}C-derived changes in solar irradiation, leading Karlén to conclude "the similarity between solar irradiation changes and climate indicate a solar influence on the Scandinavian and Greenland climates." He further concluded "the frequency and magnitude of changes in climate during the Holocene [i.e., the current interglacial] do not support the opinion that the climatic change of the last 100 years is unique," bluntly adding "there is no evidence of a human influence so far."

Also writing just before the turn of the century, Lockwood *et al.* (1999) analyzed measurements of the near-Earth interplanetary magnetic field to determine the total magnetic flux leaving the Sun since 1868. Their analysis showed the total flux rose by a factor of 1.41 over the 32-year period 1964–1996, whereas surrogate measurements of the interplanetary magnetic field previous to this time indicated the total flux had increased by a factor of 2.3 since 1901. These findings and others linking changes in solar magnetic activity with terrestrial climate change led the authors to state "the variation [in the total solar magnetic flux] found here stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field."

Parker (1999) noted the number of sunspots also roughly doubled since 1901, and one consequence of this phenomenon is a much more vigorous and slightly brighter Sun. Parker also drew attention to the fact that NASA spacecraft measurements had revealed the brightness (Br) of the Sun varies by the "change in $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle." During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth-century Medieval Maximum), he pointed out, brightness variations on the order of change in ΔBr/Br ≈ 0.5% typically occur (see Zhang *et al*. 1994, based on observational constraints from solar-type stars, for empirical support for the possibility of such a large-amplitude change). He noted the mean temperature (T) of the northern portion of Earth varied by 1 to 2°C in association with these variations in solar activity, stating, "we cannot help noting that ΔT/T ≈ ΔBr/Br."

Also in 1999, Chambers *et al*. (1999) noted research findings in both palaeoecology and solar science "indicate a greater role for solar forcing in Holocene climate change than has previously been recognized." They found substantial evidence within the Holocene for solar-driven variations in Earth-atmosphere processes over a range of timescales stretching from the 11-year solar cycle to century-scale events. They acknowledge the absolute solar flux variations associated with these phenomena are rather small, but they identify a number of "multiplier effects" that can operate on solar rhythms in such a way that "minor variations in solar activity can be reflected in more significant variations within the Earth's atmosphere."

The three researchers also noted nonlinear responses to solar variability are inadequately represented in (in fact, essentially ignored by) the global climate models used by the IPCC to predict future CO_2-induced global warming, while at the same time other amplifier effects are used to model the hypothesized CO_2-induced global warming of the future, where CO_2 is only an initial perturber of the climate system which, according to the IPCC, sets other more powerful forces in motion that produce the bulk of the warming.

Bard *et al*. (2000) identified some of the many types of information that have been used to reconstruct past solar variability, including "the envelope of the SSN [sunspot number] 11-year cycle (Reid, 1991), the length and decay rate of the solar cycle (Hoyt and Schatten, 1993), the structure and decay rate of individual sunspots (Hoyt and Schatten, 1993), the mean level of SSN (Hoyt and Schatten, 1993; Zhang *et al*., 1994; Reid, 1997), the solar rotation and the solar diameter (Nesme-Ribes *et al*., 1993), and the geomagnetic aa index (Cliver *et al*., 1998)." They also noted "Lean *et al*. (1995) proposed that the irradiance record could be divided into 2 superimposed components: an 11-year cycle based on the parameterization of sunspot darkening and facular brightening (Lean *et al*., 1992), and a slowly varying background derived separately from studies of Sun-like stars (Baliunas and Jastrow, 1990)," and that Solanki and Fligge (1998) had developed an even more convoluted technique.

Bard *et al*. used an entirely different approach. Rather than directly characterize some aspect of solar variability, they assessed certain consequences of that variability. Specifically, they noted magnetic fields of the solar wind deflect portions of the primary flux of charged cosmic particles in the vicinity of Earth, leading to reductions in the creation of cosmogenic nuclides in Earth's atmosphere. Consequently, they reasoned histories of the atmospheric concentrations of ^{14}C and ^{10}Be can be used as proxies for solar activity, as noted many years earlier by Lal and Peters (1967).

In employing this approach to the problem, the four researchers first created a 1,200-year history of cosmonuclide production in Earth's atmosphere from ^{10}Be measurements of South Pole ice (Raisbeck *et al*., 1990) and the atmospheric $^{14}C/^{12}C$ record as measured in tree rings (Bard *et al*., 1997). This record was converted to total solar irradiance (TSI) values by "applying a linear scaling using the TSI values published previously for the Maunder Minimum," when cosmonuclide production was 30 to 50 percent above the modern value. This process resulted in an extended TSI record suggesting, in their words, that "solar output was significantly reduced between AD 1450 and 1850, but slightly higher or similar to the present value during a period centered around AD 1200." "It could thus be argued," they say, "that irradiance variations may have contributed to the so-called 'little ice age' and 'medieval warm period.'"

But Bard *et al*. downplay their own suggestion, because, as they report, "some researchers have concluded that the 'little ice age' and/or 'medieval warm period' [were] regional, rather than global events." Noting the TSI variations they developed from their cosmonuclide data "would tend to force global effects," they concluded they could not associate this global impetus for climate change with what other people were calling regional climatic anomalies. (Chapter 4 of this report demonstrates the Little Ice Age and Medieval Warm Period were in fact global in extent.)

Updated discussions of the complexity and physics involved in the reconstruction of the TSI are found in the work of Fontenla *et al.* (2011), Shapiro *et al.* (2011), and section 2 of Soon and Legates (2013). It is important to contrast these in-depth studies with other TSI reconstruction studies used by the IPCC, which are based on rather questionable statistical correlations: See, for example, equation 4 in

Steinhilber *et al.* (2009), where the inter-calibration, originally published in Figure 4c of Frohlich (2009), between TSI and the so-called open magnetic field strength was based on only three data points.

Rozelot (2001) conducted a series of analyses designed to determine whether phenomena related to variations in the radius of the Sun may have influenced Earth's climate over the past four centuries. He found "at least over the last four centuries, warm periods on the Earth correlate well with smaller apparent diameter of the Sun and colder ones with a bigger Sun." Although the results of this study were correlative and did not identify a physical mechanism capable of inducing significant climate change on Earth, Rozelot reports the changes in the Sun's radius are "of such magnitude that significant effects on the Earth's climate are possible."

Rigozo *et al.* (2001) created a history of sunspot numbers for the past 1,000 years "using a sum of sine waves derived from spectral analysis of the time series of sunspot number R_Z for the period 1700–1999," and from this record they derived the strengths of parameters related to aspects of solar variability. The researchers state "the 1000-year reconstructed sunspot number reproduces well the great maximums and minimums in solar activity, identified in cosmonuclides variation records, and, specifically, the epochs of the Oort, Wolf, Sporer, Maunder, and Dalton Minimums, as well [as] the Medieval and Modern Maximums," the last of which they describe as "starting near 1900."

The mean sunspot number for the Wolf, Sporer, and Maunder Minimums was 1.36. For the Oort and Dalton Minimums it was 25.05; for the Medieval Maximum it was 53.00; and for the Modern Maximum it was 57.54. Compared with the average of the Wolf, Sporer, and Maunder Minimums, therefore, the mean sunspot number of the Oort and Dalton Minimums was 18.42 times greater; that of the Medieval Maximum was 38.97 times greater; and that of the Modern Maximum was 42.31 times greater. Similar strength ratios for the solar radio flux were 1.41, 1.89, and 1.97, respectively. For the solar wind velocity the corresponding ratios were 1.05, 1.10, and 1.11, and for the southward component of the interplanetary magnetic field they were 1.70, 2.54, and 2.67.

Both the Medieval and Modern Maximums in sunspot number and solar variability parameters stand out above all other periods of the past thousand years, with the Modern Maximum slightly besting the Medieval Maximum. These authors from Brazil and Puerto Rico recently updated (see Echer *et al.* 2012) their analysis using NASA Goddard Institute for Space Studies temperature records and found a stronger statistical correlation of the surface temperature with the sunspot number data record in the 22-year Hale magnetic cycle band, with lags from zero to four years, than in the correlation in the 11-year solar cycle band.

Noting several spacecraft have monitored total solar irradiance (TSI) for the past 23 years, with at least two of them operating simultaneously at all times, and that TSI measurements made from balloons and rockets supplement the satellite data, Frohlich and Lean (2002) compared the composite TSI record with an empirical model of TSI variations based on known magnetic sources of irradiance variability, such as sunspot darkening and brightening, after which they described how "the TSI record may be extrapolated back to the seventeenth century Maunder Minimum of anomalously lower solar activity, which coincided with the coldest period of the Little Ice Age." This exercise "enables an assessment of the extent of post-industrial climate change that may be attributable to a varying Sun, and how much the Sun might influence future climate change."

Frohlich and Lean state "warming since 1650 due to the solar change is close to 0.4°C, with pre-industrial fluctuations of 0.2°C that are seen also to be present in the temperature reconstructions." It would appear solar variability can explain a significant portion of the warming of Earth in recovering from the global chill of the Little Ice Age. With respect to the future, the two solar scientists state, "solar forcing is unlikely to compensate for the expected forcing due to the increase of anthropogenic greenhouse gases which are projected to be about a factor of 3–6 larger." The magnitude of that anthropogenic forcing, however, has been computed by many different approaches to be much smaller than the value employed by Frohlich and Lean in making this comparison (Idso, 1998).

Douglass and Clader (2002) used multiple regression analysis to separate surface and atmospheric temperature responses to solar irradiance variations over the past two-and-a-half solar cycles (1979–2001) from temperature responses produced by variations in ENSO and volcanic activity. Based on the satellite-derived lower tropospheric temperature record, they evaluated the sensitivity (*k*) of temperature (T) to solar irradiance (I), where temperature sensitivity to solar irradiance is defined as $k = \Delta T/\Delta I$, obtaining the result of $k = 0.11 \pm 0.02$°C/(W/m^2). Similar analyses based on the radiosonde temperature record of Parker *et al*. (1997) and the surface air temperature records of Jones *et al*. (2001) and Hansen and Lebedeff (1987, with updates) produced *k* values of 0.13, 0.09, and 0.11°C/(W/m^2), respectively, with the identical standard error of ± 0.02°C/(W/m^2). In addition, they reported White *et al*. (1997) derived a decadal timescale solar sensitivity of 0.10 ± 0.02°C/(W/m^2) from a study of upper ocean temperatures over the period 1955–1994 and Lean and Rind (1998) derived a value of 0.12 ± 0.02°C/(W/m^2) from a reconstructed paleo-temperature record spanning the period 1610–1800.

Douglass and Clader concluded, "the close agreement of these various independent values with our value of 0.11 ± 0.02 [°C/(W/m^2)] suggests that the sensitivity *k* is the same for both decadal and centennial time scales and for both ocean and lower tropospheric temperatures." They further suggest if these values of *k* hold true for centennial time scales, which appears to be the case, their high-end value implies a surface warming of 0.2°C over the past 100 years in response to the 1.5 W/m^2 increase in solar irradiance inferred by Lean (2000) for this period. This warming represents approximately one-third of the total increase in global surface air temperature estimated by Parker *et al*. (1997), 0.55°C, and Hansen *et al*. (1999), 0.65°C, for the same period. It does not, however, include potential indirect effects of more esoteric solar climate-affecting phenomena, such as those from cosmic rays as discussed in Section 3.2 of this chapter, that also could have been operative over this period.

Foukal (2002) analyzed the findings of space-borne radiometry and reported "variations in total solar irradiance, S, measured over the past 22 years, are found to be closely proportional to the difference in projected areas of dark sunspots, AS, and of bright magnetic plage elements, APN, in active regions and in enhanced network." They also found "this difference varies from cycle to cycle and is not simply related to cycle amplitude itself," which suggests there is "little reason to expect that S will track any of the familiar indices of solar activity." On the other hand, he notes, "empirical modeling of spectro-radiometric observations indicates that the variability of solar ultraviolet flux, FUV, at wavelengths shorter than approximately 250 nm, is determined mainly by APN alone."

Using daily data from the Mt. Wilson Observatory covering the period 1905–1984 and partially overlapping data from the Sacramento Peak Observatory that extended through 1999, Foukal derived time series of total solar and UV irradiances between 1915 and 1999, which he then compared with global temperature data for that period. He reported, "correlation of our time series of UV irradiance with global temperature, T, accounts for only 20% of the global temperature variance during the 20th century" but "correlation of our total irradiance time series with T accounts statistically for 80% of the variance in global temperature over that period."

The UV findings of Foukal were not impressive, but the results of his total solar irradiance analysis were, leading him to state "the possibility of significant driving of twentieth century climate by total irradiance variation cannot be dismissed." Although the magnitude of the total solar effect was determined to be "a factor 3–5 lower than expected to produce a significant global warming contribution based on present-day climate model sensitivities," what Foukal calls the "high correlation between S and T" strongly suggests changes in S largely determine changes in T, confirmation of which likely awaits only what he refers to as an "improved understanding of possible climate sensitivity to relatively small total irradiance variation."

Willson and Mordvinov (2003) analyzed total solar irradiance (TSI) data obtained from different satellite platforms over the period 1978–2002, attempting to resolve various small but important inconsistencies among them. In doing so, they recongized "construction of TSI composite databases will not be without its controversies for the foreseeable future." Nevertheless, their most interesting result, in the estimation of the two researchers, was their confirmation of a +0.05%/decade trend between the minima separating solar cycles 21–22 and 22–23, which they say "appears to be significant."

Willson and Mordvinov say the finding of the 0.05 percent/decade minimum-to-minimum trend "means that TSI variability can be caused by unknown mechanisms other than the solar magnetic activity cycle," which means "much longer time scales for TSI variations are therefore a possibility," which they say "has obvious implications for solar forcing of climate." Undiscovered long-term variations in total solar irradiance could explain centennial-scale climate variability, which Bond *et al*. (2001) already have demonstrated to be related to solar activity, as well as the millennial-scale climatic oscillation that pervades both glacial and interglacial periods (Oppo *et al*., 1998; Raymo *et al*., 1998).

Like Willson and Mordvinov, Foukal (2003) acknowledged "recent evidence from ocean and ice cores suggests that a significant fraction of the variability in northern hemisphere climate since the last Ice Age correlates with solar activity (Bond *et al*., 2001)," while noting "a recent reconstruction of S [total solar irradiance] from archival images of spots and faculae obtained daily from the Mt. Wilson Observatory in California since 1915 shows remarkable agreement with smoothed global temperature in the 20th century," citing his own work of 2002. He acknowledged the observed variations in S between 1978 and 2002 were not large enough to explain the observed temperature changes on Earth within the context of normal radiative forcing and proceeded to consider the status of research into subjects that might explain this situation. He reviewed then-current knowledge relative to the idea that "the solar impact on climate might be driven by other variable solar outputs of ultraviolet radiation or plasmas and fields via more complex mechanisms than direct forcing of tropospheric temperature" and concluded, "we cannot rule out multi-decadal variations in S sufficiently large to influence climate, yet overlooked so far through limited sensitivity and time span of our present observational techniques."

Citing the work of Herman and Goldberg (1978), Pittock (1983), Hoyt and Schatten (1997), and van Loon and Labitzke (2000), Thejll *et al*. (2003) note "apparent relations between solar activity, or parameters closely related to solar activity, and climate data have often been reported." Noting further that a substantial portion of Northern Hemispheric climate variability is associated with the North Atlantic Oscillation (NAO), as described by Hurrell *et al*. (2001), they report the activity of the NAO has been found to be related to solar-geomagnetic parameters (Bucha and Bucha, 1998; Boberg and Lundstedt, 2002; Kodera, 2002).

Thejll *et al*. examined spatial and temporal relationships among the geomagnetic index (*Ap*), the NAO, stratospheric geopotential height, and sea level pressure, revealing "significant correlations between *Ap* and sea-level pressures and between *Ap* and stratospheric geopotential heights are found for the period 1973–2000," but "for the period 1949–1972 no significant correlations are found at the surface while significant correlations still are found in the stratosphere." By using "Monte Carlo simulations of the statistical procedures applied to suitable surrogate data," they also concluded these correlations are due to the existence of a "real physical link." They also noted in the 1973–2000 period only the winter season series are significantly correlated, which they say "is consistent with the notion that the solar-climate link works through the stratosphere."

Thejll *et al*. stated their findings may be explained in two different ways: either the influence of the Sun increased through time, reaching a strong enough level in the 1970s to make the correlations they studied become statistically significant, or the state of the atmosphere changed in the 1970s, becoming more sensitive to the solar influence than it had been. Their findings strengthen the case for solar-induced perturbations being propagated downward from the stratosphere to the troposphere (Hartley *et al*., 1998; Carslaw *et al*., 2002).

Ineson *et al.* (2011) modeled the effects of realistic solar UV (200–320 nm) irradiance changes between solar activity minima and maxima in the stratosphere and mesosphere, finding weaker westerly winds during the winters with a less active Sun that may drive cold winters in Northern Europe and the United States and mild winters over Southern Europe and Canada, as observed in recent years. The observational analyses by Hood *et al.* (2013) add insight into the specific regional patterns of the near-surface responses that likely originated from the solar UV forcing of ozone and related wind-thermal fields in the stratosphere. These authors note "the observational analyses … provide additional evidence that a surface climate response to 11-yr solar forcing during the boreal winter season is detectable in global SLP and SST records extending back to the 19th century. The response is most clearly detected in the Pacific sector where a positive solar SLP response anomaly is obtained over the Aleutian region and a corresponding positive SST response anomaly extends across the midlatitude North Pacific ... The SLP response in the Arctic is generally negative supporting the hypothesis that the solar response is similar to a positive Arctic Oscillation mode. However, only a weak and marginally significant SST response is obtained in the equatorial eastern Pacific so the response differs from that which characterizes a La Niña event ... Analyses of the observed response as a function of phase lag indicate that the solar SLP response evolves from a predominately negative AO structure a few years prior to solar maximum to a predominately positive AO structure at and following solar maximum. ... The amplitudes of the Aleutian SLP response anomaly and the corresponding positive

SST anomaly maximize at zero lag."

As Hood *et al.* (2013) declared, "in general, models should be validated by observations rather than the other way around."

To be sure, some of the Sun-climate relation studies have been challenged. In 2004, Damon and Laut (2004) reported what they described as errors made by Friis-Christensen and Lassen (1991), Svensmark and Friis-Christensen (1997), Svensmark (1998), and Lassen and Friis-Christensen (2000) in their presentation of solar activity data correlated with terrestrial temperature data. The Danish scientists' error, in the words of Damon and Laut, was "adding to a heavily smoothed ('filtered') curve, four additional points covering the period of global warming, which were only partially filtered or not filtered at all." This in turn led to an apparent dramatic increase in solar activity over the last quarter of the twentieth century that closely matched the equally dramatic rise in temperature manifest by the Northern Hemispheric temperature reconstruction of Mann *et al*. (1998, 1999) over the same period. With the acquisition of additional solar activity data in subsequent years, however, and with what Damon and Laut called the proper handling of the numbers, the late twentieth century dramatic increase in solar activity disappears.

This new result, to quote Damon and Laut, means "the sensational agreement with the recent global warming, which drew worldwide attention, has totally disappeared." In reality, however, it is only the agreement with the last quarter-century of the discredited Mann *et al*. "hockey stick" temperature history that has disappeared. This new disagreement is important, for the Mann *et al*. temperature reconstruction is likely in error over this period of time. (See Chapter 4.)

Using a nonlinear non-stationary time series technique called empirical mode decomposition, Coughlin and Tung (2004) analyzed monthly mean geopotential heights and temperatures obtained from Kalnay *et al*. (1996) from 1000 hPa to 10 hPa over the period January 1958 to December 2003. This work revealed the existence of five oscillations and a trend in both data sets. The fourth of these oscillations has an average period of 11 years and indicates enhanced warming during times of maximum solar radiation. As the two researchers describe it, "the solar flux is positively correlated with the fourth modes in temperature and geopotential height almost everywhere [and] the overwhelming picture is that of a positive correlation between the solar flux and this mode throughout the troposphere."

Coughlin and Tung concluded "the atmosphere warms during the solar maximum almost everywhere over the globe." And the unfailing omnipresent impact of this small forcing (a 0.1 percent change in the total energy output of the Sun from cycle minimum to maximum) suggests any longer-period oscillations of the solar inferno could be causing the even greater centennial- and millennial-scale oscillations of temperature observed in paleo-temperature data from around the world.

Widespread measurements have been made since the late 1950s of the flux of solar radiation received at the surface of Earth, and nearly all of these measurements reveal a sizeable decline in the surface receipt of solar radiation that was not reversed until the mid-1980s, as noted by Wild *et al*. (2005). During this time, there was also a noticeable dip in Earth's surface air temperature, after which temperatures rose at a rate and to a level of warmth the IPCC claims were without precedent over the past one to two millennia, and which they attribute to similarly unprecedented increases in greenhouse gas concentrations, mostly notably CO_2.

This reversal of the decline in the amount of solar radiation incident upon Earth's surface, in the words of Wild *et al*., "is reconcilable with changes in cloudiness and atmospheric transmission and may substantially affect surface climate." "Whereas the decline in solar energy could have counterbalanced the increase in down-welling longwave energy from the enhanced greenhouse effect before the 1980s," they note, "the masking of the greenhouse effect and related impacts may no longer have been effective thereafter, enabling the greenhouse signals to become more evident during the 1990s." Qualitatively, this scenario sounds plausible, but when the magnitude of the increase in the surface-received flux of solar radiation over the 1990s is considered, the statement is seen to be rather disingenuous.

Over the range of years for which high-quality data were available to them (1992–2002), Wild *et al*. determined the mean worldwide increase in clear-sky insolation averaged 0.68 Wm^{-2} per year, which increase they found to be "comparable to the increase under all-sky conditions." Consequently, for that 10-year period, these data suggest the total increase in solar radiation received at the surface of Earth should have been something on the order of 6.8 Wm^{-2}, not significantly different from what is implied by the satellite and "Earthshine" data of Palle *et al*. (2004), although the satellite data of Pinker *et al*. (2005)

suggest an increase only about a third as large for this period.

Putting these numbers in perspective, Charlson *et al*. (2005) report the longwave radiative forcing provided by all greenhouse gas increases since the beginning of the industrial era has amounted to only 2.4 Wm^{-2}, citing the work of Anderson *et al*. (2003), while Palle *et al*. say "the latest IPCC report argues for a 2.4 Wm^{-2} increase in CO_2 longwave forcing since 1850." The longwave forcing of greenhouse gases over the 1990s thus would have been but a fraction of a fraction of the observed increase in the contemporary receipt of solar radiation at the surface of Earth. To suggest, as Wild *et al*. do, that the increase in insolation experienced at the surface of Earth over the 1990s may have enabled anthropogenic greenhouse gas signals of that period to become more evident seems incongruous, as their suggestion implies the bulk of the warming of that period was due to increases in greenhouse gas concentrations, when the solar component of the temperature forcing was clearly much greater. This incongruity is exacerbated by the fact that methane concentrations rose ever more slowly over this period, apparently stabilizing near the period's end (see Chapter 2). Consequently, a much more logical conclusion would be that the primary driver of the global warming of the 1990s was the large increase in global surface-level insolation.

Soon (2005) explored the question of which variable was the dominant driver of twentieth-century temperature change in the Arctic—rising atmospheric CO_2 concentrations or variations in solar irradiance—by examining what roles the two variables may have played in decadal, multidecadal, and longer-term variations in surface air temperature (SAT). He performed a number of statistical analyses on a composite Arctic-wide SAT record constructed by Polyakov *et al*. (2003), global CO_2 concentrations taken from estimates given by the NASA GISS climate modeling group, and a total solar irradiance (TSI) record developed by Hoyt and Schatten (1993, updated by Hoyt in 2005) for the period 1875–2000.

These analyses indicated a much stronger statistical relationship between SATs and TSI than between SATs and CO_2. Solar forcing generally explained more than 75 percent of the variance in decadal-smoothed seasonal and annual Arctic SATs, whereas CO_2 forcing explained only between 8 and 22 percent of the variance. Wavelet analysis further supported the case for solar forcing of the SAT record, revealing similar time-frequency characteristics for annual and seasonally averaged temperatures at decadal and multidecadal time scales. By contrast, wavelet analysis gave little or no indication of a CO_2 forcing of Arctic SSTs.

Lastovicka (2006) summarized recent advancements in the field, saying "new results from various space and ground-based experiments monitoring the radiative and particle emissions of the Sun, together with their terrestrial impact, have opened an exciting new era in both solar and atmospheric physics," stating "these studies clearly show that the variable solar radiative and particle output affects the Earth's atmosphere and climate in many fundamental ways."

Bard and Frank (2006) examined "changes on different time scales, from the last million years up to recent decades," and in doing so assessed recent claims that "the variability of the Sun has had a significant impact on global climate." The two researchers conclude the role of solar activity in causing climate change "remains unproven." But they state in the concluding sentence of their abstract, "the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: the so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500-1800)."

Beer *et al*. (2006) explored solar variability and its possible effects on Earth's climate, focusing on two types of variability in the flux of solar radiation incident on Earth. The first type, in their words, "is due to changes in the orbital parameters of the Earth's position relative to the Sun induced by the other planets," which arises from gravitational perturbations that "induce changes with characteristic time scales in the eccentricity (~100,000 years), the obliquity (angle between the equator and the orbital plane, ~40,000 years) and the precession of the Earth's axis (~20,000 years)." The second type of variability is due to variability within the Sun itself.

With respect to the latter variability, the three researchers point out direct observations of total solar irradiance above Earth's atmosphere have been made over only the past quarter-century, whereas observations of sunspots have been made and recorded for approximately four centuries. In between the time scales of these two types of measurements fall neutron count rates and aurora counts. Therefore, ^{10}Be and other cosmogenic radionuclides (such as ^{14}C)—stored in ice, sediment cores, and tree rings—

currently provide our only means of inferring solar irradiance variability on a millennial time scale. These cosmogenic nuclides "clearly reveal that the Sun varies significantly on millennial time scales and most likely plays an important role in climate change." In reference to their ^{10}Be-based derivation of a 9,000-year record of solar modulation, Beer *et al*. note its "comparison with paleoclimatic data provides strong evidence for a causal relationship between solar variability and climate change."

Nicola Scafetta, a research scientist in the Duke University physics department, and Bruce West, chief scientist in the mathematical and information science directorate of the U.S. Army Research Office in Research Triangle Park, North Carolina, developed (Scafetta and West, 2006a) "two distinct TSI reconstructions made by merging in 1980 the annual mean TSI proxy reconstruction of Lean *et al*. (1995) for the period 1900–1980 and two alternative TSI satellite composites, ACRIM (Willson and Mordvinov, 2003), and PMOD (Frohlich and Lean, 1998), for the period 1980–2000," after which they used a climate sensitivity transfer function to create twentieth century temperature histories. Their results suggested the Sun contributed some 46 to 49 percent of the 1900–2000 warming of Earth. Considering there may have been uncertainties of 20 to 30 percent in their sensitivity parameters, the two researchers suggest the Sun may have been responsible for as much as 60 percent of the twentieth century temperature rise.

Scafetta and West say the role of the Sun in twentieth century global warming has been significantly underestimated by the climate modeling community, with various energy balance models producing estimates of solar-induced warming over this period that are "two to ten times lower" than what they found. The two researchers say "the models might be inadequate because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular." They also note "theoretical models usually acknowledge as solar forcing only the direct TSI forcing," thereby ignoring "possible additional climate effects linked to solar magnetic field, UV radiation, solar flares and cosmic ray intensity modulations." It also should be noted some of these phenomena may to some degree be independent of, and thereby add to, the simple TSI forcing Scafetta and West employed, suggesting the totality of solar activity effects on climate may be even greater than what they calculated.

In a second study published that year, Scafetta and West (2006b) pointed out nearly all attribution studies begin with predetermined forcing and feedback mechanisms in the models they employ. "One difficulty with this approach," according to Scafetta and West, "is that the feedback mechanisms and alternative solar effects on climate, since they are only partially known, might be poorly or not modeled at all." Consequently, "to circumvent the lack of knowledge in climate physics," they adopt "an alternative approach that attempts to evaluate the total direct plus indirect effect of solar changes on climate by comparing patterns in the secular temperature and TSI reconstructions," where "a TSI reconstruction is not used as a radiative forcing, but as a proxy [for] the entire solar dynamics." They proceed on the assumption that "the secular climate sensitivity to solar change can be phenomenologically estimated by comparing ... solar and temperature records during the pre-industrial era, when, reasonably, only a negligible amount of anthropogenic-added climate forcing was present" and "the Sun was the only realistic force affecting climate on a secular scale."

Scafetta and West used the Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005), three alternative TSI proxy reconstructions developed by Lean *et al*. (1995), Lean (2000), and Wang *et al*. (2005), and a scale-by-scale transfer model of climate sensitivity to solar activity changes they developed (Scafetta and West, 2005, 2006a). They found a "good correspondence between global temperature and solar induced temperature curves during the pre-industrial period, such as the cooling periods occurring during the Maunder Minimum (1645–1715) and the Dalton Minimum (1795–1825)." In addition, they note since the time of the seventeenth century solar minimum, "the Sun has induced a warming of $\Delta T \sim 0.7$ K" and "this warming is of the same magnitude [as] the cooling of $\Delta T \sim 0.7$ K from the medieval maximum to the 17th century minimum." This finding, they write, "suggests the presence of a millenarian solar cycle, with ... medieval and contemporary maxima, driving the climate of the last millennium," as was first suggested fully three decades ago by Eddy (1976) in his seminal study of the Maunder Minimum.

Scafetta and West say their work provides substantive evidence for the likelihood that "solar change effects are greater than what can be explained by several climate models," citing Stevens and North (1996), the Intergovernmental Panel on Climate Change (2001), Hansen *et al*. (2002), and Foukal *et* *al*. (2004), and they note a solar change "might trigger several climate feedbacks and alter the greenhouse gas (H_2O, CO_2, CH_4, etc.) concentrations, as 420,000 years of Antarctic ice core data would also suggest (Petit *et al*., 1999)," once again reiterating "most of the Sun-climate coupling mechanisms are probably still unknown" and "might strongly amplify the effects of small solar activity increase." The researchers note in the twentieth century there was "a clear surplus warming" above and beyond what is suggested by their solar-based temperature reconstruction, such that something in addition to the Sun may have been responsible for approximately 50 percent of the total global warming since 1900.

This anomalous increase in temperature, it could be argued, was due to anthropogenic greenhouse gas emissions. However, Scafetta and West say the temperature difference since 1975, where the most noticeable part of the discrepancy occurred, may have been due to "spurious non-climatic contamination of the surface observations such as heat-island and land-use effects (Pielke *et al*., 2002; Kalnay and Cai, 2003)," which they say is also suggested by "an anomalous warming behavior of the global average land temperature vs. the marine temperature since 1975 (Brohan *et al*., 2006)."

In their next paper, Scafetta and West (2007) reconstructed a phenomenological solar signature (PSS) of climate for the Northern Hemisphere for the past four centuries that matches relatively well the instrumental temperature record since 1850 and the paleoclimate temperature proxy reconstruction of Moberg (2005). The period from 1950 to 2010 showed excellent agreement between 11- and 22-year PSS cycles when compared to smoothed average global temperature data and the global cooling that occurred since 2002.

Continuing their effort to identify a solar signal in Earth's global temperature record, in the March 2008 issue of *Physics Today* Scafetta and West (2008) began by noting the IPCC concludes "the contribution of solar variability to global warming is negligible, to a certainty of 95%," which would appear to stack the deck heavily against their being successful. Whereas "the statistical variability in Earth's average temperature is interpreted as noise" by most climate modelers and "thought to contain no useful information," Scafetta and West proposed "the variations in Earth's temperature are not noise, but contain substantial information about the source of variability," which they suggest is total solar irradiance, or TSI. The two researchers further suggest "variations in TSI are indicative of the Sun's turbulent dynamics," as represented by "changes in the number, duration, and intensity of solar flares and sunspots, and by the intermittency in the time intervals between dark spots and bright faculae," which variability has the capacity to "move the global temperature up and down for tens or even hundreds of years."

In providing support for their hypothesis, Scafetta and West point out "both the fluctuations in TSI, using the solar flare time series as a surrogate, and Earth's average temperature time series are observed to have inverse power-law statistical distributions," and the inverse power-law index "turns out to be the same for both the solar flare and temperature anomaly time series," citing the work of Scafetta and West (2003). This suggests "the statistics of the temperature anomalies inherit the statistical structure that was evident in the intermittency of the solar flare data." This finding led the two researchers to conclude "the Sun is influencing climate significantly more than the IPCC report claims" and "the current anthropogenic contribution to global warming is significantly overestimated." Citing Scafetta and West (2007), they "estimate that the Sun could account for as much as 69% of the increase in Earth's average temperature, depending on the TSI reconstruction used."

In 2009, Scafetta and Richard C. Willson, senior research scientist at Columbia's Center for Climate Systems Research, addressed whether TSI increased from 1980 to 2002 (Scafetta and Willson, 2009). The IPCC assumed there was no increase by adopting the TSI satellite composite produced by the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (see Frohlich, 2006). PMOD assumed the NIMBUS7 TSI satellite record artificially increased its sensitivity during the ACRIM-gap (1999.5–1991.75) and therefore reduced the NIMBUS7 record by 0.86 W/m^2 during the ACRIM-gap period; consequently, the TSI results changed little since 1980. This PMOD adjustment of NIMBUS7 TSI satellite data was never acknowledged by the experimental teams (Willson and Mordvinov, 2003; supporting material in Scafetta and Willson, 2009).

Scafetta and Willson proposed to resolve the ACRIM-gap calibration controversy by developing a TSI model using a proxy model based on variations of the surface distribution of solar magnetic flux designed by Krivova *et al.* (2007) to bridge the two-year gap between ACRIM1 and ACRIM2. They use this to bridge "mixed" versions of ACRIM and

PMOD TSI before and after the ACRIM-gap. Both "mixed" models show, in the authors' words, "a significant TSI increase of 0.033%/decade between the solar activity minima of 1986 and 1996, comparable to the 0.037% found in the TSI satellite ACRIM composite." They conclude "increasing TSI between 1980 and 2000 could have contributed significantly to global warming during the last three decades. Current climate models have assumed that TSI did not vary significantly during the last 30 years and have, therefore, underestimated the solar contribution and overestimated the anthropogenic contribution to global warming."

Krivova *et al*. (2007) noted "strong interest" in the subject of long-term variations of total solar irradiance or TSI "due to its potential influence on global climate," suggesting "only a reconstruction of solar irradiance for the pre-satellite period with the help of models can aid in gaining further insight into the nature of this influence." They developed a history of TSI "from the end of the Maunder minimum [about AD 1700] to the present based on variations of the surface distribution of the solar magnetic field," which was "calculated from the historical record of the sunspot number using a simple but consistent physical model," e.g., that of Solanki *et al*. (2000, 2002).

Krivova *et al*. report their model "successfully reproduces three independent data sets: total solar irradiance measurements available since 1978, total photospheric magnetic flux since 1974, and the open magnetic flux since 1868," which was "empirically reconstructed using the geomagnetic *aa*-index." Based on this model, they calculated an increase in TSI since the Maunder minimum somewhere in the range of 0.9-1.5 Wm^{-2}, which encompasses the results of several independent reconstructions derived over the past few years. In the final sentence of their paper, however, they note "all the values we obtain are significantly below the ΔTSI values deduced from stellar data and used in older TSI reconstructions," the results of which range from 2 to 16 Wm^{-2}.

Although there remains a degree of uncertainty about the true magnitude of the TSI change experienced since the end of the Maunder Minimum, the wide range of possible values suggests long-term TSI variability cannot be rejected as a plausible cause of the majority of the global warming seen since the Little Ice Age. The results of many of the studies reviewed in this section argue strongly for this scenario, while others suggest it is the only explanation that fits all the data.

Goode and Pallé (2007) state at the outset of their paper, "we know that there are terrestrial imprints of the solar cycle" even when "the implied changes in solar irradiance seem too weak to induce an imprint." They try to discern how such a small solar signal might induce such a large climatic response. They reviewed data shedding light on two important parameters of climate change—solar irradiance and terrestrial reflectance—which together determine the net sunlight absorbed by the Earth-ocean-atmosphere system, thereby setting the stage for the system's ultimate thermal response to the forcing they provide.

In attempting to "illustrate the possibilities of a Sun-albedo link," Goode and Pallé conclude "reflectance changes like the ones observed during the past two decades, if maintained over longer time periods, are sufficient to explain climate episodes like the 'Little Ice Age' without the need for significant solar irradiance variations." While they say their analysis of the problem "cannot be used to argue for a solar cycle dependence," they also note "it is … difficult to dismiss the possibility of a solar-albedo link."

Goode and Pallé conclude, "regardless of its possible solar ties," Earth's large-scale reflectance "is a much more variable climate parameter than previously thought and, thus, deserves to be studied in as much detail as changes in the Sun's output or changes in the Earth's atmospheric infrared emission produced by anthropogenic greenhouse gases." They note "long-term records of the Earth's reflectance will provide crucial input for general circulation climate models, and will significantly increase our ability to assess and predict climate change."

Shaviv (2008) attempted to quantify solar radiative forcing using oceans as a calorimeter. He evaluated three independent measures of net ocean heat flux over five decades, sea level change rate from twentieth century tide gauge records, and sea surface temperature. He found a "very clear correlation between solar activity and sea level" including the 11-year solar periodicity and phase, with a correlation coefficient of r=0.55. He also found "the total radiative forcing associated with solar cycles variations is about 5 to 7 times larger than those associated with the TSI variations, thus implying the necessary existence of an amplification mechanism, though without pointing to which one."

Shaviv argues "the sheer size of the heat flux, and the lack of any phase lag between the flux and the driving force further implies that it cannot be part of an atmospheric feedback and very unlikely to be part of a coupled atmosphere-ocean oscillation mode. It must therefore be the manifestation of real variations in the global radiative forcing." This provides "very strong support for the notion that an amplification mechanism exists. Given that the CRF [Cosmic Ray Flux]/climate links predicts the correct radiation imbalance observed in the cloud cover variations, it is a favorable candidate." These results, Shaviv says, "imply that the climate sensitivity required to explain historic temperature variations is smaller than often concluded."

Pallé *et al.* (2009) reanalyzed the overall reflectance of sunlight from Earth ("Earthshine") and recalibrated the CERES satellite data to obtain consistent results for Earth's solar reflectance. According to the authors, "Earthshine and FD [flux data] analyses show contemporaneous and climatologically significant increases in the Earth's reflectance from the outset of our Earthshine measurements beginning in late 1998 roughly until mid-2000. After that and to date, all three show a roughly constant terrestrial albedo, except for the FD data in the most recent years. Using satellite cloud data and Earth reflectance models, we also show that the decadal-scale changes in Earth's reflectance measured by Earthshine are reliable and are caused by changes in the properties of clouds rather than any spurious signal, such as changes in the Sun-Earth-Moon geometry."

Ohmura (2009) reviewed surface solar irradiance at 400 sites across the globe, finding a brightening phase from the 1920s to 1960s, followed by a 20-year dimming phase from 1960 to 1980. Then there was another 15-year brightening phase from 1990 to 2005. Ohmura finds "aerosol direct and indirect effects played about an equal weight in changing global solar radiation. The temperature sensitivity due to radiation change is estimated at 0.05 to 0.06 K/(W m^{-2})."

Long *et al.* (2009) analyzed "all-sky and clear-sky surface downwelling shortwave radiation and bulk cloud properties" from 1995 through 2007. They "show that widespread brightening has occurred over the continental United States ... averaging about 8 W m^{-2}/decade for all-sky shortwave and 5 W m^{-2}/decade for the clear-sky shortwave. This all-sky increase is substantially greater than the (global) 2 W m^{-2}/decade previously reported..." Their "results show changes in dry aerosols and/or direct aerosol effects alone cannot explain the observed changes in surface shortwave (SW) radiation, but it is likely that changes in cloudiness play a significant role."

These observations by Shaviv, Pallé, Ohmura, and Long *et al.* each point to major variations in Earth's radiative budget caused by changes in aerosols and clouds. Both are affected by natural and anthropogenic causes, including aircraft, power plants, cars, cooking, forest fires, and volcanoes. Natural forces—solar activity and cosmic rays—also modulate clouds. Later in this chapter, in Section 3.3.5, empirical evidence uncovered by Soon *et al.* (2011) for the simultaneous multidecadal modulation of the TSI and near-surface solar radiation from a unique sunshine duration record by the Japanese Meteorological Agency is discussed. When GCMs ignore or underestimate causes or modulation by solar cycles, magnetic fields, and/or cosmic rays, they overestimate the climate sensitivity of anthropogenic impacts.

Scafetta (2012) developed an "astronomical-based empirical harmonic climate model" that assumed Earth's climate system is resonating with, or synchronized to, a set of natural frequencies of the solar system (Scafetta, 2010, 2011). He indicates the major hypothesized mechanism upon which the model is based is that "the planets, in particular Jupiter and Saturn, induce solar or heliospheric oscillations that induce equivalent oscillations in the electromagnetic properties of the [Earth's] upper atmosphere," which in turn induces similar cycles in cloud cover and terrestrial albedo, "forcing the climate to oscillate in the same way." Essentially Scafetta proposes tidal effects of the large gas planets influence the solar fusion process and energy distribution across the solar system, which would ultimately also result in changes in climate on our planet Earth. Considering that lunar tidal effects cause major cyclical perturbations on Earth such as tidal ebb and flow of up to 21m, the model of planetary tides influencing the solar system does not seem unreasonable.

Scafetta tested the performance of this model "against all general circulation climate models (GCMs) adopted by the IPCC (2007) to interpret climate change during the last century." This analysis yielded a number of intriguing results. The solar scientist found "the GCMs fail to reproduce the major decadal and multi-decadal oscillations found in the global surface temperature record from 1850 to 2011," but his harmonic model (which uses cycles having periods of 9.1, 10–10.5, 20–21 and 60–62 years) "is found to well reconstruct the observed climate oscillations from 1850 to 2011." Scafetta also found his model "is able to forecast the climate oscillations from 1950 to 2011 using the data covering the period 1850–1950, and vice versa."

Scafetta concludes the results he obtained "reinforce previous claims that the relevant physical mechanisms that explain the detected climatic cycles are still missing in the current GCMs and that climate variations at the multi-decadal scales could be astronomically induced and, in first approximation, could be forecast," further noting "the presence of these large natural cycles can be used to correct the IPCC projected anthropogenic warming trend for the 21st century." In doing so, he found "the temperature may not significantly increase during the next 30 years, mostly because of the negative phase of the 60-year cycle," and IPCC-projected anthropogenic CO_2 emissions would imply a global warming of only 0.3–1.2°C by 2100, as opposed to the 1.0–3.6°C projected by the IPCC. This conclusion also would hold true if the 60-year climate cycle were a purely internal cycle ("autocycle") originating and resonating inside the climate system without major external forcing. This model is also favored by other scientists (see for example Tsonis *et al*. 2007; Douglass 2010; Wyatt *et al*. 2012). He also has tested the CMIP5 models (Scafetta 2013a,b).

Another important synthesis of the study of the Sun-climate relation was provided by Akasofu (2010), who examined a wide range of climatic records—including temperature proxies, lake and river ice break-up dates, sea ice and sea level changes, and glaciers—to document that the current warm period is largely a natural recovery from the Little Ice Age (dated by Akasofu to be between 1200–1400 and 1800–1850). Akasofu provides evidence suggesting a relatively lower solar irradiance existed during the Little Ice Age interval.

As demonstrated in the many studies referenced above, it is fairly certain the Sun was responsible for creating multi-centennial global cold and warm periods in the past, and it is quite plausible that modern fluctuations in solar output are responsible for the majority, if not entirety, of the global warming the planet experienced during the past century or so.

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3.2 Cosmic Rays

The study of extraterrestrial climatic forcing factors is primarily a study of phenomena related to the Sun. Historically, this field of inquiry began with the work of Milankovitch (1920, 1941), who linked the cyclical glaciations of the past million years to the receipt of solar radiation at the surface of Earth as modulated by variations in Earth's orbit and rotational characteristics. Subsequent investigations implicated other solar phenomena that operate on both shorter and longer timescales. This section reviews the findings of studies that involve galactic cosmic rays (GCRs).

The IPCC *Fifth Assessment Report* (AR5) does not consider cosmic rays as being capable of producing a significant forcing on Earth's climate. The Second Order Draft (SOD) of AR5, for example, opines "there is high confidence (medium evidence and high agreement*)* that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way" (p. 8.33 of the SOD of AR5, dated October 5, 2012). Furthermore, the draft claims "no robust association between changes in cosmic rays and cloudiness has been identified," while adding "in the event that such an association exists, it is very unlikely to be due to cosmic ray-induced nucleation of new aerosol particles" (p. 19 of the Technical Summary of the SOD).

By contrast, the following review of the literature clearly demonstrates the viability of GCRs as an important climate-forcing agent, where many key components of this hypothesis have been verified. The GCR theory is a growing climate forcing the IPCC must reckon with.

The field of GCR research begins with the original publication of Svensmark and Friis-Christensen (1997). A good summary can be found in the review paper of Svensmark (2007), director of the Center for Sun-Climate Research of the Danish National Space Center, who describes how he and his colleagues experimentally determined ions released to the atmosphere by galactic cosmic rays act as catalysts that significantly accelerate the formation of ultra-small clusters of sulfuric acid and water molecules that constitute the building blocks of cloud condensation nuclei. Svensmark also discusses the complex chain of expected atmospheric interactions, in particular how, during periods of greater solar activity, greater shielding of Earth occurs associated with a strong solar magnetic field. That shielding results in less cosmic rays penetrating to the lower atmosphere of the Earth, resulting in fewer cloud condensation nuclei being produced and thus fewer and less reflective low-level clouds occurring. More solar radiation is thus absorbed the surface of Earth, resulting in increasing near-surface air temperatures and global warming.

Svensmark provides support for key elements of this scenario with graphs illustrating the close correspondence between global low-cloud amount and cosmic-ray counts over the period 1984–2004. He also notes the history of changes in the flux of galactic cosmic rays estimated since 1700, which correlates well with Earth's temperature history over the same time period, starting from the latter portion of the Maunder Minimum (1645–1715), when Svensmark says "sunspots were extremely scarce and the solar magnetic field was exceptionally weak," and continuing on through the twentieth century, over which last hundred-year interval, as noted by Svensmark, "the Sun's coronal magnetic field doubled in strength."

Svensmark also cites the work of Bond *et al.* (2001), who in studying ice-rafted debris in the North Atlantic Ocean determined, in Svensmark's words, "over the past 12,000 years, there were many icy intervals like the Little Ice Age" that "alternated with warm phases, of which the most recent were the Medieval Warm Period (roughly AD 900–1300) and the Modern Warm Period (since 1900)." As Bond's 10-member team indicates, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

In expanding the timescale further, while highlighting the work of Shaviv (2002, 2003a) and Shaviv and Veizer (2003), Svensmark (2007) presents plots of reconstructed sea surface temperature anomalies and relative cosmic ray flux over the past 550 million years (Svensmark's Figure 8), during which time the solar system experienced four passages through the spiral arms of the Milky Way galaxy, with the climatic data showing "rhythmic cooling of the Earth whenever the Sun crossed the galactic midplane, where cosmic rays are locally most intense." Svensmark concludes "stellar winds and magnetism are crucial factors in the origin and viability of life on wet Earth-like planets," as are "ever-changing galactic environments and star-formation rates." Shaviv (2003b) went so far as to sketch the qualitative idea for a plausible resolution of the early faint Sun paradox by arguing for a lower cosmic ray flux from a strong solar wind (i.e., more cloud coverage to keep early Earth relatively warmer than it would be otherwise) during the very early portion of Earth's 4.5 billion-year history.

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark in his overview of the cosmic ray-climate connection. Lockwood *et al.* (1999), for example, examined measurements of the near-Earth interplanetary magnetic field in an effort to determine the total magnetic flux leaving the Sun since 1868. They showed the total magnetic flux from the Sun rose by a factor of 1.41 over the period 1964–1996, while surrogate measurements of the interplanetary magnetic field previous to this time indicate total magnetic flux had risen by a factor of 2.3 since 1901. The three researchers stated the variation in the total solar magnetic flux they found "stresses the importance of understanding the connections between the Sun's output and its magnetic field and between terrestrial global cloud cover, cosmic ray fluxes and the heliospheric field."

In commenting on the work of Lockwood *et al*., Parker (1999) noted additional solar considerations also may have played an important part in the modern rise of global temperature. He noted the number of sunspots doubled over the prior 100 years, and one consequence of this phenomenon would have been "a much more vigorous Sun" that was slightly brighter. Parker pointed out spacecraft measurements suggest the brightness (Br) of the Sun varies by an amount $\Delta Br/Br \approx 0.15\%$, in step with the 11-year magnetic cycle. During times of much reduced activity of this sort (such as the Maunder Minimum of 1645–1715) and much increased activity (such as the twelfth century Medieval Maximum), he notes, brightness variations on the order of $\Delta Br/Br \approx 0.5\%$ typically occur. He also notes the mean temperature (T) of the northern portion of the Earth varied by 1 to 2°C in association with these variations in solar activity, stating finally, "we cannot help noting that $\Delta T/T \approx \Delta Br/Br$." Furthermore, knowing sea surface temperatures are influenced by the brightness of the Sun and had risen since 1900, Parker writes, "one wonders to what extent the solar brightening [of the past century] has contributed to the increase in atmospheric temperature and CO_2" over that period. Parker reaches what he deems an "inescapable conclusion": "We will have to know a lot more about the Sun and the terrestrial atmosphere before we can understand the nature of the contemporary changes in climate."

Recent findings from a Swiss team of researchers, Shapiro *et al.* (2001), indicate electromagnetic solar irradiation also probably increased much more than previously thought from the Little Ice Age until today. Based on their new study, the scientists assume an increase six times higher than the value used by the IPCC (Shapiro *et al*., 2011; Lockwood, 2011).

Digging deeper into the cosmic ray subject, Feynman and Ruzmaikin (1999) investigated twentieth century changes in the intensity of cosmic rays incident upon Earth's magnetopause and their transmission through the magnetosphere to the upper troposphere. This work revealed "the intensity of cosmic rays incident on the magnetopause has decreased markedly during this century" and "the pattern of cosmic ray precipitation through the magnetosphere to the upper troposphere has also changed."

Solanki *et al*. (2000) developed a model of the long-term evolution of the Sun's large-scale magnetic field and compared its predictions against two proxy measures of this parameter. The model proved successful in reproducing the observed century-long doubling of the strength of the part of the Sun's magnetic field that reaches out from the Sun's surface into interplanetary space. It also indicated there is a direct connection between the length of the 11-year sunspot cycle and secular variations in solar activity that occur on timescales of centuries, such as the Maunder Minimum of the latter part of the seventeenth century, when sunspots were few and Earth was in the midst of the Little Ice Age.

One year later, using cosmic ray data recorded by ground-based neutron monitors, global precipitation data from the Climate Predictions Center Merged Analysis of Precipitation project, and estimates of monthly global moisture from the National Centers for Environmental Prediction reanalysis project, Kniveton and Todd (2001) set out to evaluate whether there is empirical evidence to support the hypothesis that solar variability (represented by changes in cosmic ray flux) is linked to climate change (manifested by changes in precipitation and precipitation efficiency) over the period 1979–1999. They determined there is "evidence of a statistically strong relationship between cosmic ray flux, precipitation and precipitation efficiency over ocean surfaces at mid to high latitudes," since variations in both precipitation and precipitation efficiency for mid to high latitudes showed a close relationship in both phase and magnitude with variations in cosmic ray flux, varying 7 to 9 percent during the solar cycle of the 1980s. Other potential forcing factors were ruled out due to poorer statistical relationships.

The same year, Bond *et al*. (2001) published the results of their study of ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). Based on analyses of deep-sea sediment cores that yielded abundance changes in time of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern, and with the help of an accelerator mass spectrometer date, a number of recurring alternate periods of relative cold and warmth that wended their way through the 12,000-year expanse of the Holocene. The mean duration of the several complete climatic cycles thus delineated was 1,340 years, and the two last cold and warm nodes of the latter oscillations, in the words of Bond *et al*., were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period.'"

The signal accomplishment of the scientists' study was the linking of these millennial-scale climate oscillations—and their embedded centennial-scale oscillations—with similar-scale oscillations in cosmogenic nuclide production, known to be driven by contemporaneous oscillations in solar activity. Bond *et al*. reported, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum." They concluded "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the Sun are experienced throughout the world.

With respect to the near-global extent of the climatic impact of the solar radiation variations they detected, Bond *et al.* reference studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating "the footprint of the solar impact on climate we have documented extend[s] from polar to tropical latitudes." They also note "the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence." They further note their findings support previous suggestions that both the Little Ice Age and Medieval Warm Period "may have been partly or entirely linked to changes in solar irradiance."

Bond *et al*. reiterate that the oscillations in drift-ice they studied "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system." At two of their coring sites, they identified a series of such cyclical variations that extended throughout all of the previous interglacial and were "strikingly similar to those of the Holocene." Here they could also have cited the work of Oppo *et al*. (1998), who observed similar climatic oscillations in a sediment core that covered the span of time from 340,000 to 500,000 years before present, and that of Raymo *et al*. (1998), who pushed back the time of the cycles' earliest known occurrence to well over one million years ago.

How do the small changes in solar radiation inferred from the cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth's global climate? Bond *et al*. describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth's surface, provoking changes in North Atlantic deep water formation that alter the thermohaline circulation of the global ocean. They speculate "the solar signals thus may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint." Concluding their landmark paper, the researchers write the results of their study "demonstrate that the Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output," noting their work "supports the presumption that solar variability will continue to influence climate in the future."

The following year, Sharma (2002) presented the case for an even longer oscillation in solar magnetism—on the order of 100,000 years—that might bear responsibility for the recurring glacial/interglacial periods. This potential finding, which has been established for only two of the putative 100,000-year cycles and could turn out to be spurious, is based upon the fact that the production of ^{10}Be in Earth's atmosphere is affected by the intensity of magnetic activity at the surface of the Sun as well as Earth's geomagnetic dipole strength.

Using data pertaining to these factors obtained from several different sources, Sharma began his analysis by compiling 200,000-year histories of relative geomagnetic field intensity (from natural remnant magnetizations of marine sediments) and normalized atmospheric ^{10}Be production rate (also from marine sediments). Then, with the help of a theoretical construct describing the ^{10}Be production rate as a function of the solar modulation of galactic cosmic rays (arising from variations in magnetic activity at the surface of the Sun) and Earth's geomagnetic field intensity, he created a 200,000-year history of the solar modulation factor.

This history reveals the existence of significant periods of both enhanced and reduced solar activity; comparing it with the marine δ^{18}O record (a proxy for global ice volume and, therefore, Earth's mean surface air temperature), Sharma found the two histories are strongly correlated. As he describes it, "the solar activity has a 100,000-year cycle in phase with the $\delta^{18}O$ record of glacial-interglacial cycles," such that "the long-term solar activity and Earth's surface temperature appear to be directly related." Throughout the 200,000-year period, Sharma notes, "the Earth has experienced a warmer climate whenever the Sun has been magnetically more active" and "at the height of the last glacial maximum the solar activity was suppressed." It is therefore easy for Sharma to make the final connection, setting forth as a new hypothesis the proposal that "variations in solar activity control the 100,000-year glacial-interglacial cycles," just as they also appear to control other embedded and cascading climatic cycles.

In a contemporaneous study, Carslaw *et al.* (2002) began an essay on "Cosmic Rays, Clouds, and Climate" by noting the intensity of cosmic rays varies by about 15 percent over a solar cycle due to changes in the strength of the solar wind, which carries a weak magnetic field into the heliosphere that partially shields Earth from low-energy galactic charged particles. When this shielding is at a minimum, allowing more cosmic rays to impinge upon the planet, more low clouds have been observed to cover Earth, producing a tendency for lower temperatures to occur. When the opposite condition is true, a warmer Earth is to be expected because less low cloud cover is formed by this proposed mechanism.

The three researchers further note the total variation in low cloud amount over a solar cycle is about 1.7 percent, which corresponds to a change in the planet's radiation budget of about one watt per square meter (1 Wm^{-2}). This change, they say, "is highly significant when compared ... with the estimated radiative forcing of 1.4 Wm^{-2} from anthropogenic CO_2 emissions." Because of the short length of a solar cycle (11 years), the large thermal inertia of the world's oceans dampens the much greater global temperature change that would have occurred as a result of this radiative forcing had it been spread out over a much longer period of time, so the actual observed warming is a little less than 0.1°C.

Much of Carslaw *et al.*'s review focuses on mechanisms by which cosmic rays might induce the synchronous low cloud cover changes observed to accompany changes in cosmic ray intensity. The researchers begin by briefly describing the three principal mechanisms that have been suggested to function as links between solar variability and changes in Earth's weather: changes in total solar irradiance that provide variable energy input to the lower atmosphere, changes in solar ultraviolet radiation and its interaction with ozone in the stratosphere that couple dynamically to the lower atmosphere, and changes in cloud processes having significance for condensation nucleus abundances, thunderstorm electrification and thermodynamics, and ice formation in cyclones.

Focusing on the third of these mechanisms, Carslaw *et al.* note cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes. They further refine their focus to concentrate on ways by which cosmic-ray-produced ions may affect cloud droplets and ice particles. Here, they concentrate on two specific topics, what they call the ion-aerosol clear-air mechanism and the ion-aerosol near-cloud mechanism. Their review suggests what we know about these subjects is very much less than what we could know about them. Many scientists, as they describe it, believe "it is inconceivable that the lower atmosphere can be globally bombarded by ionizing radiation without producing an effect on the climate system."

Carslaw *et al.* point out cosmic ray intensity declined by about 15 percent during the past century "owing to an increase in the solar open magnetic flux by more than a factor of 2." They further report "this 100-year change in intensity is about the same magnitude as the observed change over the last solar cycle." In addition, it should be noted the cosmic ray intensity was already much lower at the start of the twentieth century than it was just after the start of the nineteenth century, when many historical records and climate proxies indicate the planet began its nearly two-century-long recovery from the Little Ice Age.

These observations strongly suggest solar-mediated variations in the intensity of cosmic rays bombarding Earth may indeed be responsible for the temperature variations of the past three centuries. They provide a much better fit to the temperature data than do atmospheric CO_2 data; and as Carslaw *et al.* remark, "if the cosmic ray-cloud effect is real, then these long-term changes of cosmic ray intensity could substantially influence climate." It is this possibility, they say, that makes it "all the more important to understand the cause of the cloudiness variations," as the cosmic ray-cloud connection may hold the key to resolving what they call this "fiercely debated geophysical phenomenon."

One year later, and noting Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), and Palle Bago and Butler (2000) had derived positive relationships between global cosmic ray intensity and low-cloud amount from infrared cloud data contained in the International Satellite Cloud Climatology Project (ISCCP) database for the years 1983–1993, Marsden and Lingenfelter (2003) used that database for the expanded period 1983–1999 to see if a similar relationship could be detected via cloud amount measurements made in the visible spectrum. This work revealed "a positive correlation at low altitudes, which is consistent with the positive correlation between global low clouds and cosmic ray rate seen in the infrared."

It is appropriate here to point out there are contemporary and active disagreements within the scientific community with respect to the empirical basis for the cosmic-ray-low cloud relation originally reported by Svensmark and Friis-Christensen (1997) and in updates by colleagues. Soon *et al.* (2000) provided such a challenge to Svensmark's empirical finding and pointed to another promising solar-weather-upper atmospheric relation involving the physico-chemical interactions of the relativistic electron precipitation events with NO_y molecules in the middle atmosphere first described in Callis *et al.* (1998). Further insights and details, as discussed in Paul Prikryl and colleagues (2009a; 2009b), involving the solar wind, aurora, and atmospheric gravity waves, also may be important in explaining physical realities and adding confidence in understanding Sun-weather-climate relations.

In 2003, Shaviv and Veizer (2003) provided additional support for a cosmic ray influence on climate, suggesting from two-thirds to three-fourths of the variance in Earth's temperature (T) over the past 500 million years may be attributable to cosmic ray flux (CRF) variations due to solar system passages through the spiral arms of the Milky Way galaxy. They presented several half-billion-year histories of T, CRF, and atmospheric CO_2 concentrations derived from various types of proxy data and found none of the CO_2 curves showed any clear correlation with the T curves, suggesting "CO_2 is not likely to be the principal climate driver." By contrast, they discovered the T trends displayed a dominant cyclic component on the order of 135 ± 9 million years and "this regular pattern implies that we may be looking at a reflection of celestial phenomena in the climate history of Earth."

That possibility is borne out by their identification of a similar CRF cycle of 143 ± 10 million years, together with the fact that the large cold intervals in the T records "appear to coincide with times of high CRF," a correspondence that would be expected from the likely chain of events: high CRF ==> more low-level clouds ==> greater planetary albedo ==> colder climate, as described by Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000), Palle Bago and Butler (2000), and Marsden and Lingenfelter (2003).

What do these findings suggest about the role of atmospheric CO_2 variations with respect to global temperature change? Shaviv and Veizer begin their analysis by stating the conservative approach is to assume the entire residual variance not explained by measurement error is due to CO_2 variations. Doing so, they found a doubling of the air's CO_2 concentration could account for only about a 0.5°C increase in T. This result differs considerably, in their words, "from the predictions of the general circulation models, which typically imply a CO_2 doubling effect of ~1.5–5.5°C" but is "consistent with alternative lower estimates of 0.6-1.6°C (Lindzen, 1997)." Shaviv and Veizer's result is even more consistent with the results of the eight empirically based "natural experiments" of Idso (1998), which yield an average warming of about 0.4°C for a 300 to 600 ppm doubling of the atmosphere's CO_2 concentration.

In another important test of a critical portion of the cosmic ray-climate connection theory, Usoskin *et al*. (2004b) compared the spatial distributions of low cloud amount (LCA) and cosmic ray-induced ionization (CRII) over the globe for the period 1984–2000. They used observed LCA data from the ISCCP-D2 database limited to infrared radiances and employed CRII values calculated by Usoskin *et al*. (2004a) at 3 km altitude, which corresponds roughly to the limiting altitude below which low clouds form. This work revealed "the LCA time series can be decomposed into a long-term slow trend and inter-annual variations, the latter depicting a clear 11-year cycle in phase with CRII." In addition, they found "a one-to-one relation between the relative variations of LCA and CRII over the latitude range 20–55°S and 10–70°N" and "the amplitude of relative variations in LCA was found to increase polewards, in accordance with the amplitude of CRII variations." These findings of the five-member team of Finnish, Danish, and Russian scientists provide substantial evidence for a solar-cosmic ray linkage (the 11-year cycle of CRII) and a cosmic ray-cloud linkage (the in-phase cycles of CRII and CLA), making the full solar activity/cosmic ray/low cloud/climate change hypothesis appear to be rather robust.

In a review of the temporal variability of solar phenomena, Lean (2005) made an important but disturbing point about climate models and the Sun-climate connection: "A major enigma is that general circulation climate models predict an immutable climate in response to decadal solar variability, whereas surface temperatures, cloud cover, drought, rainfall, tropical cyclones, and forest fires show a definite correlation with solar activity (Haigh, 2001, Rind, 2002)."

Lean begins her review by noting the beginning of the Little Ice Age "coincided with anomalously low solar activity (the so-called Sporer and Maunder minima)" and "the latter part coincided with both low solar activity (the Dalton minimum) and volcanic eruptions." After discussing the complexities of this potential relationship, she considers another alternative: "Or might the Little Ice Age be simply the most recent cool episode of millennial climate-oscillation cycles?" Lean cites evidence revealing the sensitivity of drought and rainfall to solar variability, stating climate models are unable to reproduce what she called the "plethora" of Sun-climate connections. She notes simulations with climate models yield decadal and centennial variability even in the absence of external forcing, stating "arguably, this very sensitivity of the climate system to unforced oscillation and stochastic noise predisposes it to nonlinear responses to small forcings such as by the Sun."

Lean reports "various high-resolution paleo-climate records in ice cores, tree rings, lake and ocean sediment cores, and corals suggest that changes in the energy output of the Sun itself may have contributed to Sun-Earth system variability," citing the work of Verschuren *et al*. (2000), Hodell *et al*. (2001), and Bond *et al*. (2001). She notes "many geographically diverse records of past climate are coherent over time, with periods near 2,400, 208, and 90 years that are also present in the ^{14}C and ^{10}Be archives," as these isotopes (produced at the end of a complex chain of interactions initiated by galactic cosmic rays) contain information about various aspects of solar activity (Bard *et al*., 1997).

Veretenenko *et al*. (2005) examined the potential influence of galactic cosmic rays (GCR) on the long-term variation of North Atlantic sea-level pressure over the period 1874–1995. Their comparisons of long-term variations in cold-season (October-March) sea-level pressure with different solar/geophysical indices revealed increasing sea-level pressure coincided with a secular rise in solar/geomagnetic activity accompanied by a decrease in GCR intensity. By contrast, long-term decreases in sea-level pressure were observed during periods of decreasing solar activity and rising GCR flux. Spectral analysis further supported a link between sea-level pressure, solar/geomagnetic activity, and GCR flux, as similar spectral characteristics (periodicities) were present among all data sets at time scales from approximately 10 to 100 years.

These results support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. Veretenenko *et al*. hypothesize GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development. Although scientists lack a complete understanding of many solar/GCR-induced climatic influences, this study highlights the growing need for such relationships to be explored. As it and others have shown, small changes in solar output can indeed induce significant changes in Earth's climate.

More recent analyses by Veretenenko and Ogurtsov (2012) and Georgieva *et al.* (2012) have added details to the intricate relationship between solar-cosmic-ray activity, plausibly mediated by geomagnetic activity, and weather-climate circulation patterns around the North Atlantic and elsewhere. Veretenenko and Ogurtsov (2012) emphasize the 60-year periodicity in some of the sun-climate relationship, while Georgieva *et al.* (2012) worked toward an explanation of the occasional time-dependence of the statistical correlations between solar and climatic variables.

Also working in the North Atlantic region, Macklin *et al*. (2005) developed what they call "the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ^{14}C-dated British flood deposits," after which they compared their reconstructed flood history "with high-resolution proxy-climate records from the North Atlantic region, northwest Europe and the British Isles to critically test the link between climate change and flooding." They determined "the majority of the largest and most widespread recorded floods in Great Britain have occurred during cool, moist periods" and "comparison of the British Holocene palaeoflood series ... with climate reconstructions from tree-ring patterns of subfossil bog oaks in northwest Europe also suggests that a similar relationship between climate and flooding in Great Britain existed during the Holocene, with floods being more frequent and larger during relatively cold, wet periods." In addition, they find "an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ^{14}C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods."

Usoskin *et al*. (2005) note "the variation of the cosmic ray flux entering Earth's atmosphere is due to a combination of solar modulation and geomagnetic shielding, the latter adding a long-term trend to the varying solar signal." They also note "the existence of a geomagnetic signal in the climate data would support a direct effect of cosmic rays on climate." They evaluate this proposition by reproducing 1,000-year reconstructions of two notable solar-heliospheric indices derived from cosmogenic isotope data—the sunspot number and the cosmic ray flux (Usoskin *et al*., 2003; Solanki *et al*., 2004)—and creating a new 1,000-year air temperature history of the Northern Hemisphere by computing annual means of six different thousand-year surface air temperature series—those of Jones *et al*. (1998), Mann *et al*. (1999), Briffa (2000), Crowley (2000), Esper *et al*. (2002), and Mann and Jones (2003). In comparing these three series (solar activity, cosmic ray flux, and air temperature), Usoskin *et al*. found they "indicate higher temperatures during times of more intense solar activity (higher sunspot number, lower cosmic ray flux)." In addition, they report three different statistical tests "consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with sunspots," suggesting something in addition to solar activity must have been influencing the cosmic ray flux in order to make the flux the better correlate of temperature.

Noting Earth's geomagnetic field strength would be a natural candidate for this "something," Usoskin *et al*. compared their solar activity, cosmic ray, and temperature reconstructions with two long-term reconstructions of geomagnetic dipole moment obtained from the work of Hongre *et al*. (1998) and Yang *et al*. (2000). This effort revealed that between AD 1000 and 1700, when there was a substantial downward trend in air temperature associated with a less substantial downward trend in solar activity, there was also a general downward trend in geomagnetic field strength. Usoskin *et al*. suggested the substantial upward trend of cosmic ray flux needed to sustain the substantial rate of observed cooling (which was more than expected in light of the slow decline in solar activity) was likely due to the positive effect on the cosmic ray flux produced by the decreasing geomagnetic field strength.

After 1700, the geomagnetic field strength continued to decline, but air temperature began to rise. This "parting of company" between the two parameters, according to Usoskin *et al*., occurred because "the strong upward trend of solar activity during that time overcompensate[d] [for] the geomagnetic effect," leading to a significant warming. In addition, some of the warming of the past century or so (15–20 percent) may have been caused by the concomitant increase in the atmosphere's CO_2 content, which would have complemented the warming produced by the solar activity and further decoupled the upward trending temperature from the declining geomagnetic field strength.

Together, these observations tend to strengthen the hypothesis that cosmic ray variability was a significant driver of changes in Earth's surface air temperature over the past millennium, and that this forcing was driven primarily by variations in solar activity modulated by the more slowly changing geomagnetic field strength of the planet, which sometimes strengthened the solar forcing and sometimes worked against it. The results leave room for only a small impact of anthropogenic CO_2 emissions on twentieth century warming.

Versteegh (2005) reviewed what was known about past climatic responses to solar forcing and their geographical coherence based upon proxy records of temperature and the cosmogenic radionuclides ^{10}Be and ^{14}C, which provide a measure of magnetized plasma emissions from the Sun that affect Earth's exposure to galactic cosmic rays. Versteegh concluded "proxy records provide ample evidence for climate change during the relatively stable and warm Holocene" and "all frequency components attributed to solar variability re-occur in proxy records of environmental change." The author emphasized "the ~90 years Gleisberg and ~200 years Suess cycles in the ^{10}Be and ^{14}C records" as well as "the ~1500 years Bond cycle which occurs in several proxy records [and] could originate from the interference between centennial-band solar cycles." Versteegh concludes "long-term climate change during the preindustrial [era] seems to have been dominated by solar forcing," and the long-term response to solar forcing "greatly exceeds unforced variability."

Harrison and Stephenson (2005) note that because the net global effect of clouds is cooling (Hartman, 1993), any widespread increase in the amount of overcast days could reduce air temperature globally, while local overcast conditions could do so locally. They compared the ratio of diffuse to total solar radiation (the diffuse fraction, DF), measured daily at 0900 UT at Whiteknights, Reading (UK) from 1997–2004, with the traditional subjective determination of cloud amount made by a human observer as well as with daily average temperature. They compared the diffuse fraction measured at Jersey between 1968 and 1994 with corresponding daily mean neutron count rates measured at Climax, Colorado (USA), which provide a globally representative indicator of the galactic cosmic ray flux. They report, "across the UK, on days of high cosmic ray flux (which occur 87% of the time on average) compared with low cosmic ray flux, (i) the chance of an overcast day increases by 19% ± 4%, and (ii) the diffuse fraction increases by 2% ± 0.3%." In addition, they found "during sudden transient reductions in cosmic rays (e.g. Forbush events), simultaneous decreases occur in the diffuse fraction."

The two researchers note the last of these observations indicates diffuse radiation changes are "unambiguously due to cosmic rays." They also report, "at Reading, the measured sensitivity of daily average temperatures to DF for overcast days is -0.2 K per 0.01 change in DR." Consequently, they suggest the well-known inverse relationship between galactic cosmic rays and solar activity will lead to cooling at solar minima, and "this might amplify the effect of the small solar cycle variation in total solar irradiance, believed to be underestimated by climate models (Stott *et al*., 2003) which neglect a cosmic ray effect." In addition, although the effect they detect is small, they say it is "statistically robust" and the cosmic ray effect on clouds likely "will emerge on long time scales with less variability than the considerable variability of daily cloudiness."

Based on information that indicated a solar activity-induced increase in radiative forcing of 1.3 Wm^{-2} over the twentieth century (by way of cosmic ray flux reduction), plus the work of others (Hoyt and Schatten, 1993; Lean *et al*., 1995; Solanki and Fligge, 1998) that indicated a globally averaged solar luminosity increase of approximately 0.4 Wm^{-2} over the same period, Shaviv (2005) calculated an overall and ultimately solar activity-induced warming of 0.47°C (1.7 Wm^{-2} x 0.28°C per Wm^{-2}) over the twentieth century. Added to the 0.14°C of anthropogenic-induced warming, the calculated total warming of the twentieth century thus came to 0.61°C, noted by Shaviv to be very close to the 0.57°C temperature increase said by the IPCC to have been observed over the past century. Both Shaviv's and Idso's analyses, which mesh well with real-world data of both the recent and distant past, suggest only 15 to 20 percent (0.10°C/0.57°C) of the observed warming of the twentieth century can be attributed to the rise in the air's CO_2 content.

In another study from 2005, de Jager (2005) reviewed what was known at the time about the role of the Sun in orchestrating climate change over the current interglacial period, including changes that occurred during the twentieth century, focusing on the direct effects of solar irradiance variations and the indirect effects of magnetized plasma emissions.

With respect to solar irradiance variations, de Jager writes, "the fraction of the solar irradiance that directly reaches the Earth's troposphere is emitted by the solar photosphere [and] does not significantly vary." The variable part of this energy flux, as he continues, is emitted by chromospheric parts of centers of solar activity and "only directly influences the higher, stratospheric terrestrial layers," which "can only influence the troposphere by some form of stratosphere-troposphere coupling." With respect to magnetized plasma emissions, de Jager concludes "the outflow of magnetized plasma from the Sun and its confinement in the heliosphere influences the Earth's environment by modulating the flux of galactic cosmic radiation observed on Earth." He notes "cosmogenic radionuclides are proxies for this influence" and "the variable cosmic ray flux may influence climate via variable cloudiness."

Of these two phenomena, deJager seems to lean toward the latter as being the more significant. He notes the Northern Hemispheric temperature history developed by Moberg *et al*. (2005) "runs reasonably well parallel to" reconstructions of past solar variability derived from cosmogenic radionuclide concentrations, which are proxies for the outflow of magnetized plasma from the Sun. Perhaps most interesting in this regard is de Jager's observation that "never during the past ten or eleven millennia has the Sun been as active in ejecting magnetized plasma as during the second half of the twentieth century."

de Jager notes "a topical and much debated question is that of the cause of the strong terrestrial heating in the last few decades of the twentieth century," which "is usually ascribed to greenhouse warming." His review gives credence to the view that solar activity, especially that associated with the effects of ejected magnetized plasma on the galactic cosmic ray flux incident on Earth's atmosphere, could be responsible for the bulk of twentieth century warming as well as most of the major temperature swings (both up and down) of the Holocene.

Usoskin *et al*. (2006) say many solar scientists believe changes in solar activity have been responsible for significant changes in climate, but to demonstrate that a record of past variations in solar activity is required. They note "long-term solar activity in the past is usually estimated from cosmogenic isotopes, ^{10}Be or ^{14}C, deposited in terrestrial archives such as ice cores and tree rings," because "the production rate of cosmogenic isotopes in the atmosphere is related to the cosmic ray flux impinging on Earth," which "is modulated by the heliospheric magnetic field and is thus a proxy of solar activity." A nagging concern, however, is that the isotope records may suffer from what the five scientists call "uncertainties due to the sensitivity of the data to several terrestrial processes."

Noting the activity of a cosmogenic isotope in a meteorite represents "the time integrated cosmic ray flux over a period determined by the mean life of the radioisotope," Usoskin *et al*. reasoned "by measuring abundance of cosmogenic isotopes in meteorites which fell through the ages, one can evaluate the variability of the cosmic ray flux, since the production of cosmogenic isotopes ceases after the fall of the meteorite." If they could develop such a meteoritic-based cosmogenic isotope record, they posit, they could use it "to constrain [other] solar activity reconstructions using cosmogenic ^{44}Ti activity in meteorites which is not affected by terrestrial processes."

The researchers chose ^{44}Ti for this purpose because it has a half-life of about 59 years and is thus "relatively insensitive to variations of the cosmic ray flux on decadal or shorter time scales but is very sensitive to the level of the cosmic ray flux and its variations on a centennial scale." They compared the results of different long-term ^{10}Be- and ^{14}C-based solar activity reconstruction models with measurements of ^{44}Ti in 19 stony meteorites (chondrites) that fell between 1766 and 2001, as reported by Taricco *et al*. (2006). They determined "most recent reconstructions of solar activity, in particular those based on ^{10}Be data in polar ice (Usoskin *et al*., 2003, 2004c; McCracken *et al*., 2004) and on ^{14}C in tree rings (Solanki *et al*., 2004), are consistent with the ^{44}Ti data."

Dergachev *et al*. (2006) reviewed "direct and indirect data on variations in cosmic rays, solar activity, geomagnetic dipole moment, and climate from the present to 10–12 thousand years ago, [as] registered in different natural archives (tree rings, ice layers, etc.)." They found "galactic cosmic ray levels in the Earth's atmosphere are inversely related to the strength of the helio- and geomagnetic fields" and conclude "cosmic ray flux variations are apparently the most effective natural factor of climate changes on a large time scale." They note "changes in cloud processes under the action of cosmic rays, which are of importance for abundance of condensation nuclei and for ice formation in cyclones, can act as a connecting link between solar variability and changes in weather and climate." They cite numerous scientific studies indicating "cosmic rays are a substantial factor affecting weather and climate on time scales of hundreds to thousands of years."

Noting "there is evidence that solar activity variations can affect the cloud cover at Earth" but "it is still unclear which solar driver plays the most important role in the cloud formation," Voiculescu *et al.* (2006) used "partial correlations to distinguish between the effects of two solar drivers (cosmic rays and the UV irradiance) and the mutual relations between clouds at different altitudes." They found "a strong solar signal in the cloud cover," noting "low clouds are mostly affected by UV irradiance over oceans and dry continental areas and by cosmic rays over some mid-high latitude oceanic areas and moist lands with high aerosol concentration." They further state "high clouds respond more strongly to cosmic ray variations, especially over oceans and moist continental areas."

Gallet and Genevey (2007) documented what they call a "good temporal coincidence" between "periods of geomagnetic field intensity increases and cooling events" as measured in western Europe, where cooling events were "marked by glacier advances on land and increases in ice-rafted debris in [North Atlantic] deep-sea sediments." Their analyses revealed "a succession of three cooling periods in western Europe during the first millennium AD," the ages of which were "remarkably coincident with those of the main discontinuities in the history of Maya civilization," confirming the earlier work of Gallet *et al*. (2005), who had found a "good temporal coincidence in western Europe between cooling events recovered from successive advances of Swiss glaciers over the past 3,000 years and periods of rapid increases in geomagnetic field intensity," the latter of which were "nearly coeval with abrupt changes, or hairpin turns, in magnetic field direction."

Gallet and Genevey concluded "the most plausible mechanism linking geomagnetic field and climate remains a geomagnetic impact on cloud cover," whereby "variations in morphology of the Earth's magnetic field could have modulated the cosmic ray flux interacting with the atmosphere, modifying the nucleation rate of clouds and thus the albedo and Earth surface temperatures (Gallet *et al*., 2005; Courtillot *et al*., 2007)." These observations clearly suggest a global impact on climate, which is further suggested by the close relationship found to exist between "cooling periods in the North Atlantic and aridity episodes in the Middle East," as well as by the similar relationship demonstrated by Gallet and Genevey to have prevailed between periods of aridity over the Yucatan Peninsula and well-documented times of crisis in Mayan civilization.

In another study that took a look at the really big picture, painted by rhythmically interbedded limestone and shale or limestone and chert known as *rhythmites*, Elrick and Hinnov (2007) "(1) review the persistent and widespread occurrence of Palaeozoic rhythmites across North America, (2) demonstrate their primary depositional origin at millennial time scales, (3) summarize the range of paleo-environmental conditions that prevailed during rhythmite accumulation, and (4) briefly discuss the implications primary Palaeozoic rhythmites have on understanding the origin of pervasive late Neogene-Quaternary millennial-scale climate variability." They conclude "millennial-scale climate changes occurred over a very wide spectrum of paleoceanographic, paleogeographic, paleoclimatic, tectonic, and biologic conditions and over time periods from the Cambrian to the Quaternary." Given these observations, they note, "it is difficult to invoke models of internally driven thermohaline oceanic oscillations or continental ice sheet instabilities to explain their origin." Consequently, they suggest "millennial-scale paleoclimate variability is a more permanent feature of the Earth's ocean-atmosphere system, which points to an external driver such as solar forcing."

Kirkby (2008) reports "diverse reconstructions of past climate change have revealed clear associations with cosmic ray variations recorded in cosmogenic isotope archives, providing persuasive evidence for solar or cosmic ray forcing of the climate." He discusses two classes of microphysical mechanisms that have been proposed to connect cosmic rays with clouds, which interact significantly with fluxes of both solar and thermal radiation and, therefore, climate: "firstly, an influence of cosmic rays on the production of cloud condensation nuclei and, secondly, an influence of cosmic rays on the global electrical circuit in the atmosphere and, in turn, on ice nucleation and other cloud microphysical processes."

Kirkby observes "considerable progress on understanding ion-aerosol-cloud processes has been made in recent years, and the results are suggestive of a physically plausible link between cosmic rays, clouds and climate." "With new experiments planned or underway, such as the CLOUD facility at CERN," he states, "there are good prospects that we will have some firm answers to this question within the next few years." He points out, "the question of whether, and to what extent, the climate is influenced by solar and cosmic ray variability remains central to our understanding of the anthropogenic contribution to present climate change."

In another paper published the same year, Shaviv (2008) notes "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references. Nevertheless, it has been difficult for the IPCC to accept the logical derivative of this fact, that solar variations are driving major climate changes. The IPCC contends measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes. The dilemma might be resolved if some amplification mechanism were discovered, but most attempts to do so have been fraught with difficulty and met with much criticism. Shaviv, however, makes a good case for at least the existence of such an amplifier, and he points to a sensible candidate to fill this role.

Shaviv used "the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle" via "the study of three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations," each of which can be used "to consistently derive the same oceanic heat flux." He demonstrated "there are large variations in the oceanic heat content together with the 11-year solar cycle" and reports the three independent data sets "consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance," thus "implying," as he describes it, "the necessary existence of an amplification mechanism, although without pointing to which one."

Finding it difficult to resist pointing, however, Shaviv acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis, which was suggested by Ney (1959), discussed by Dickinson (1975), and championed by Svensmark (1998). Based on "correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions," this concept, according to Shaviv, "predicts the correct radiation imbalance observed in the cloud cover variations" needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle. Shaviv concludes the solar-wind modulated CRF hypothesis is "a favorable candidate" for primary instigator of the many climatic phenomena discussed in this chapter.

Knudsen and Riisager (2009), while noting "the galactic cosmic ray (GCR) flux is also modulated by Earth's magnetic field," state "if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between Earth's magnetic field and climate." In a test of this supposition, Knudsen and Riisager set out to "compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen *et al*., 2008) with proxy records for past low-latitude precipitation (Fleitman *et al*., 2003; Wang *et al*., 2005)." The first of these proxy records is derived from a speleothem $\delta^{18}O$ record obtained from stalagmite Q5 from Qunf cave in southern Oman, and the second is derived from a similar record obtained from stalagmite DA from Dongge cave in southern China.

The two researchers say the various correlations they observed over the course of the Holocene "suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment." They note the general increase in precipitation observed over the past 1,500 years in both speleothem records "cannot be readily explained by changes in summer insolation or solar activity" but "correlates very well with the rapid decrease in dipole moment observed during this period." This relationship is explained by the fact that "a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation." Knudsen and Riisager conclude, "in addition to supporting the notion that variations in the geomagnetic field may have influenced Earth's climate in the past," their study also provides support for a link "between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system."

Concurrently, Ram *et al*. (2009) focused their attention on studies of dust in the Greenland Ice Sheet Project 2, acknowledging others have shown the dust concentration in the upper 2.8 km of the ice, spanning approximately 100,000 years, "is strongly modulated at regular periods close to 11, 22, 80 and 200 years, all of which are well-known periods of solar activity" (Ram *et al*., 1998; Ram and Stolz, 1999). But they concede "an amplifying mechanism must be at work if solar influence is to be taken seriously." They go on to describe work that largely satisfies that criterion as it applies to dust variability, indicating "changes in nucleation processes in clouds associated with the cosmic ray flux (CRF) can provide the necessary amplification," which they describe in abbreviated form as "increased solar activity —> decreased cosmic ray flux —> decreased air-Earth [downward electric] current [density (*Jz*)] —> decreased contact nucleation —> decreased precipitation —> increased dust."

Since this chain of events operates via changes in cloud characteristics, Ram *et al*. (2009) conclude it provides "circumstantial evidence for a Sun/climate connection mediated by the terrestrial CRF," which "may initiate a sufficiently large amplification mechanism that can magnify the influence of the Sun on the Earth's climate beyond the traditional radiative effects." They encourage additional work to "incorporate the effects of the CRF on *Jz* (and associated nucleation processes), and the subsequent microphysical responses, into macroscopic cloud models that can then be incorporated into global climate models." Until this is done successfully, today's climate models cannot be claimed to include all processes that may be of significance to the accurate simulation of Earth's future climate. The importance of the global electric circuit for connecting the electrically induced changes in cloud microphysics and storm vorticity, as well as plausible effects on large-scale circulation, is spelled out by Tinsley and colleagues (see Tinsley *et al.* 2007; Tinsley 2012).

Henrik Svensmark and two coauthors (Svensmark *et al*. 2009), all from the National Space Institute of the Technical University of Denmark in Copenhagen, explored the consequences of Forbush decreases (FDs) in the influx of galactic cosmic rays (GCRs) produced by periodic explosive events on the Sun that result in "magnetic plasma clouds from solar coronal mass ejections that pass near the Earth and provide a temporary shield against GCRs." Based on cloud liquid water content data obtained over the world's oceans by the Special Sounder Microwave Imager, liquid water cloud fraction data obtained by the Moderate Resolution Imaging Spectroradiometer, and data on IR detection of low clouds over the ocean by the International Satellite Cloud Climate Project, as well as FD data obtained from 130 neutron monitors world-wide and the Nagoya muon detector, Svensmark *et al*. found "substantial declines in liquid-water clouds, apparently tracking the declining cosmic rays and reaching minima some [~7] days after the GCR minima." Concurrently, they also found "parallel observations by the aerosol robotic network AERONET reveal falls in the relative abundance of fine aerosol particles, which, in normal circumstances, could have evolved into cloud condensation nuclei."

The Danish scientists say their results "show global-scale evidence of conspicuous influences of solar variability on cloudiness and aerosols." They report "the loss of ions from the air during FDs reduces the cloud liquid water content over the oceans" and note "so marked was the response to relatively small variations in the total ionization" that "a large fraction of Earth's clouds could be controlled by ionization." Such observations support Svensmark's theory that solar-activity-induced decreases in GCR bombardment of Earth lead to decreases in low (<3.2 km) clouds as a result of reduced atmospheric ionization and, therefore, less fine aerosol particles that under normal circumstances could have evolved into cloud condensation nuclei that could have resulted in more low-level clouds that could have cooled the planet.

Voiculescu and Usoskin (2012) offered some guidelines for the study of solar-GCR-cloud relation: "A consensus regarding the impact of solar variability on cloud cover is far from being reached," they note. "Our results show that solar signatures in cloud cover persist in some key climate-defining regions for the entire time period [i.e., 1984–2009] and supports the idea that, if existing, solar effects are not visible at the global level and any analysis of solar effects on cloud cover (and consequently, on climate) should be done at the regional level."

Le Mouel *et al*. (2010a) examined the Sun-climate connection on a much-reduced time scale. The team of Professors Jean-Louis Le Mouel, Vincent Courtillot, and colleagues has published several papers investigating how the Sun's variable magnetic activity may affect various terrestrial phenomena, including weather and climate (see for example Kossobokov *et al*. 2010; Le Mouel *et al*. 2010b). Their 2010 publication (Le Mouel *et al*. 2010a) adds insight to the topic.

Figure 3.2.1, for example, displays unexpected and surprising correlations between the long-term variation in the amplitude (A) of the solid Earth rotation parameter (here they have adopted its well-detected semiannual variation) called length of day, and two candidate solar activity measures: sunspot number (SN) and neutron count (NC, a proxy for incoming galactic cosmic rays), obtained from a station in Moscow, Russia. They point out A and NC are inversely correlated with SN, the solar activity index, which leads A by about one year. And since galactic cosmic rays are also inversely related to sunspot number with a delay of one to two years or so, A is directly correlated to NC.

Le Mouel *et al*. explain the correlations as being due to a plausible physical link of the 11-year solar activity cycle to a systematic modulation of tropospheric zonal wind, since winds above 30 km contribute less than 20 percent of Earth's angular momentum, as proxied by A.

They also point out that, although the IPCC and others usually rule out the role of solar irradiance impact on terrestrial climate because of the small interannual changes in the solar irradiance, such an argument does not apply to the plausible link of the large seasonal incoming solar radiation in modulating the semiannual oscillations in the length-of-day amplitude. Le Mouel *et al*. say their paper "shows that the Sun can (directly or indirectly) influence tropospheric zonal mean-winds over decadal to multidecadal time scales." And noting "zonal mean-winds constitute an important element of global atmospheric circulation," they go on to suggest, "if the solar cycle can influence zonal mean-winds, then it may affect other features of global climate as well, including oscillations such as the NAO (North Atlantic Oscillation) and MJO (Madden-Julian Oscillation), of which zonal winds are an ingredient." Thus, "the cause of this forcing," as they describe it, "likely involves some combination of solar wind, galactic cosmic rays, ionosphere-Earth currents and cloud microphysics."

Takahashi *et al. (*2010) found evidence for ~27 day variation in the Outgoing Longwave Radiation data record (a proxy of cloud amount) in

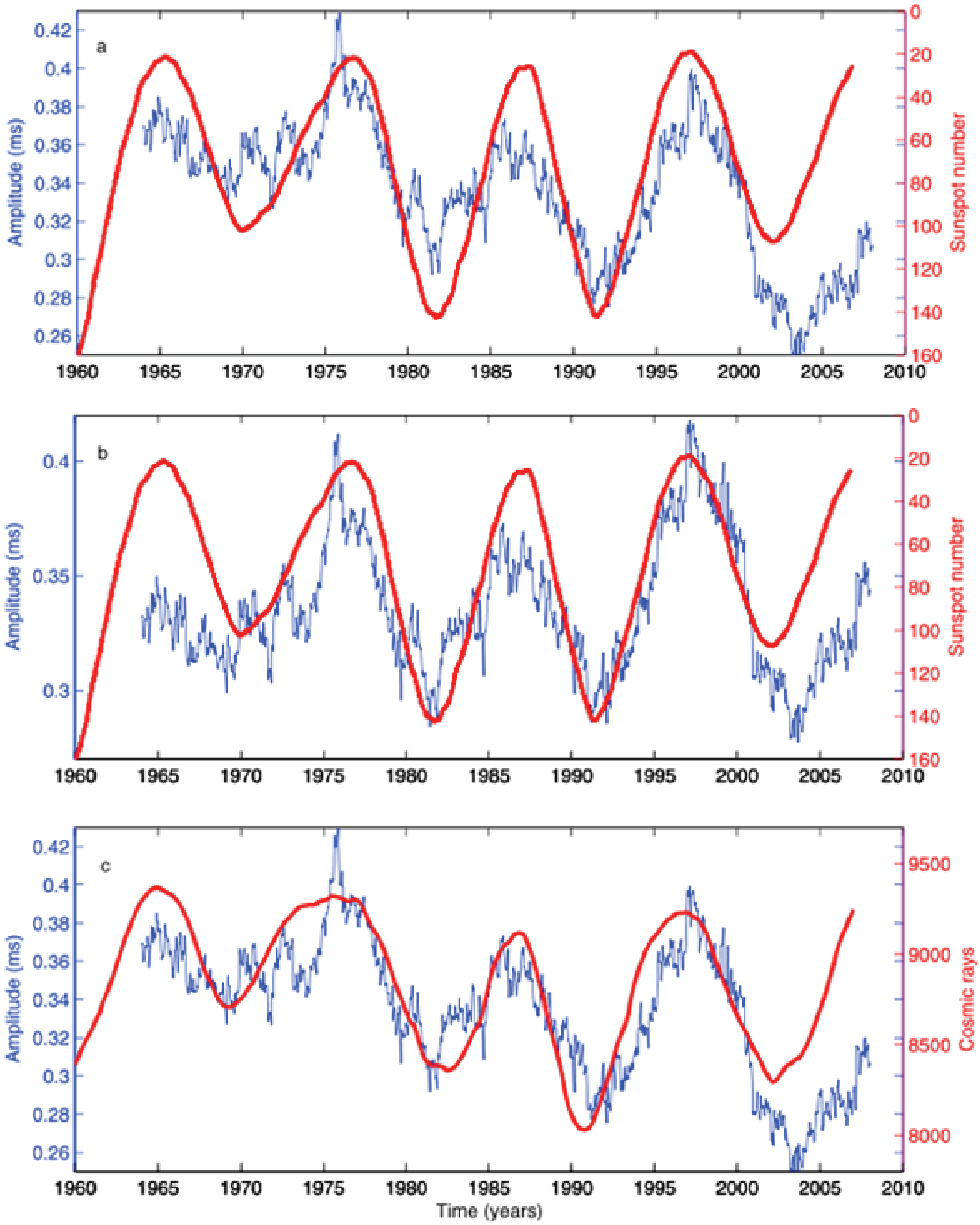

Figure 3.2.1. Correlation between the amplitude of the semiannual oscillation in length of day (blue curves with middle panel as detrended data with both top and bottom panels as original data) and various solar activity measures (sunspot numbers and proxy for galactic cosmic rays: red curves) from 1962–2009. A four-year moving-average filter was used to smooth the data series. Reprinted with permission from Le Mouel, J.-L., Kossobokov, V., and Courtillot, V. 2010b. A solar pattern in the longest temperature series from three stations in Europe. *Journal of Atmospheric and Solar-Terrestrial Physics* **72**: 62–76.

the Western Pacific warm pool region during solar activity maximum years. A significant enhancement is also found in the period of 40–60 days, corresponding to the MJO periods. A follow-up study by Hong *et al.* (2011) found further complexity in the relationship by showing the dependence of the correlations of solar rotation activity to the cloud amount on the phase of the QBO equatorial stratospheric winds. The team of Le Mouel and Courtillot follow up with the demonstration of the modulation of the MJO periods by 11-yr-like solar activity adopting both the solar UV and GCR proxies in Blanter *et al.* (2012).

Contemporaneously, Scafetta (2010) investigated less-explored solar-planetary interactions and how they might also be capable of influencing Earth's climate. Using the pattern of perturbations of the Sun's motion relative to the center of the solar system as a measure of the internal gravitational interactions of the Sun-planet system, he identified—via spectral analysis and other means—a number of clear periodic signals. A spectral decomposition of Hadley Centre climate data shows similar spectra, with the results of a spectral coherence test of the two histories being highly significant. The spectral pattern of climate model simulations does not match the solar and climatic variability patterns, whereas the output of a model based on astronomically forced cycles matches global temperature data well, and it matches ocean temperature data even better.

The mechanism behind the newly discovered suite of relationships appears to be a combination of planetary gravitational effects upon the Sun (see Scafetta 2012a,b; Scafetta and Willson, 2013a,b) that influence both direct solar irradiance and the Sun's magnetic field, plus an interaction of the magnetic fields of the other planets with Earth's magnetic field and the solar wind. Through these means the solar-terrestrial magnetic field experiences oscillations of several different frequencies, each of which exerts an influence on the intensity of cosmic rays reaching Earth and the subsequent generation of climate-changing clouds.

Two recent works by Abreu *et al.* (2012) and McCracken *et al.* (2013) reported on the interesting co-occurrences of periodic variations in the empirical solar modulation parameter (deduced from ^{14}C and ^{10}Be) and theoretical calculation of the planet-induced torque on the assumed aspherical shell of the solar tachocline. The remarkable coincidence of the five periodic changes on timescales of 88, 104, 150, 208, and 506 years should encourage further scientific investigation to find the true and correct physical mechanisms in order to explain and confirm how both the gaseous giant planets and inner terrestrial planets of our solar system together could influence the internal operation of the solar magnetic dynamo within the Sun and therefore its radiative and magnetic outputs.

One promising possibility has been proposed by Wolff and Patrone (2010), who described how the inertial motions of the Sun with respect to the barycenter of the solar system may be linked to the inner working of the solar dynamo. Wolff and Patrone also show how the orbital angular momentum of the solar inertial motion can lead to storage (and subsequent release) of potential energy within the inner solar shell through differential exchanges of mass or fluid element within the inner Sun.

The important dynamical characterization and link of the plausible planetary influences and modulations on the long-term operation of the internal solar dynamo was recently highlighted by Cionco and Campagnucci (2012). In addition, McCracken *et al.* (2013) confirm the periodic changes in millennial timescale over the past 9,400 years.

In light of the evidence presented above, the flux of galactic cosmic rays clearly wields an important influence on Earth's climate, likely much more so than that exhibited by the modern increase in atmospheric CO_2. That makes fluctuations in the Sun the primary candidate for "prime determinant" of Earth's climatic state. At the very least, these research findings invalidate the IPCC's AR5 claim that "there is high confidence (medium evidence and high agreement*)* that the GCR-ionization mechanism is too weak to influence global concentrations of cloud condensation nuclei or their change over the last century or during a solar cycle in a climatically-significant way" (p. 8.33 of the SOD of AR5, dated October 5, 2012) and that "no robust association between changes in cosmic rays and cloudiness has been identified" (p. 19 of the Technical Summary of the SOD).

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3.3 Temperature

This section examines correlations between various solar indices and temperature across the globe and for various sub-regions of the planet. These findings suggest a much larger influence of the Sun on climate forcing than is acknowledged by the IPCC. For example, mutual analysis of daily total solar irradiance (TSI) and various air temperature time series reveals important statistical variability structure common to both the solar forcing and the climate system response series. Because the length of analyzed series reaches climate scale, the result can improve our understanding about climate variability.

3.3.1 Global

The claim that anthropogenic greenhouse gas emissions have been responsible for twentieth century warming is based on what Loehle (2004) calls "the standard assumption in climate research, including the IPCC reports," that "over a century time interval there is not likely to be any recognizable trend to global temperatures (Risbey *et al*., 2000), and thus the null model for climate signal detection is a flat temperature trend with some autocorrelated noise." Loehle continues, "any warming trends in excess of that expected from normal climatic variability are then assumed to be due to anthropogenic effects." That assumption misses the possibility of significant underlying climate trends or cycles.

Loehle used a pair of 3,000-year proxy climate records with minimal dating errors to characterize the pattern of climate change over the past three millennia simply as a function of time, with no attempt to make the models functions of solar activity or any other physical variable. The first of the two temperature series was the sea surface temperature (SST) record of the Sargasso Sea, derived by Keigwin

(1996) from a study of the oxygen isotope ratios of foraminifera and other organisms contained in a sediment core retrieved from a deep-ocean drilling site on the Bermuda Rise. This record provides SST data for about every 67th year from 1125 BC to 1975 AD. The second temperature series was the ground surface temperature record derived by Holmgren *et al*. (1999, 2001) from studies of stalagmites found in a cave in South Africa, with color variations caused by changes in the concentrations of humic materials entering the region's ground water that were reliably correlated with regional near-surface air temperature.

Loehle used these two specific records because "most other long-term records have large dating errors, are based on tree rings, which are not reliable for this purpose (Broecker, 2001), or are too short for estimating long-term cyclic components of climate." Also, in a repudiation of the approach employed by Mann *et al*. (1998, 1999) and Mann and Jones (2003), he reports "synthetic series consisting of hemispheric or global mean temperatures are not suitable for such an analysis because of the inconsistent timescales in the various data sets," noting further, as a result of his own testing, "when dating errors are present in a series, and several series are combined, the result is a smearing of the signal."

Can only two temperature series reveal the pattern of global temperature change? According to Loehle, "a comparison of the Sargasso and South Africa series shows some remarkable similarities of pattern, especially considering the distance separating the two locations," suggesting "the climate signal reflects some global pattern rather than being a regional signal only." He also notes a comparison of the mean record with the South Africa and Sargasso series from which it was derived "shows excellent agreement" and "the patterns match closely." He notes "this would not be the case if the two series were independent or random."

Loehle fits seven time-series models to the two temperature series and to the average of the two series, using no data from the twentieth century. In all seven cases, good to excellent fits were obtained. As one example, the three-cycle model he fit to the averaged temperature series had a simple correlation of 0.58 and an 83 percent correspondence of peaks when evaluated by a moving window count.

Comparing the forward projections of the seven models through the twentieth century, Loehle notes six of the models "show a warming trend over the 20th century similar in timing and magnitude to the Northern Hemisphere instrumental series," and "one of the models passes right through the 20th century data." Such results suggest "20th century warming trends are plausibly a continuation of past climate patterns" and, therefore, that "anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes."

Loehle's analyses also reveal a long-term linear cooling trend of 0.25°C per thousand years since the peak of the interglacial warm period that occurred some 7,000 years ago, essentially identical to the mean value of the trend derived from seven prior assessments of its magnitude and five prior climate reconstructions. In addition, Loehle's analyses reveal the existence of the Medieval Warm Period of 800–1200 AD, which was shown to have been significantly warmer than the Current Warm Period experienced to date, as well as the existence of the Little Ice Age of 1500–1850 AD, shown to have been the coldest period of the entire 3,000-year record.

Loehle cites 16 peer-reviewed scientific journal articles documenting the existence of the Medieval Warm Period in all parts of the world and 18 other articles documenting the worldwide occurrence of the Little Ice Age. In one of the more intriguing aspects of his study—of which Loehle makes no mention—both the Sargasso Sea and South African temperature records reveal the existence of a major temperature spike beginning in the early 1400s. This abrupt warming pushed temperatures considerably above the peak warmth of the twentieth century before falling back to pre-spike levels in the mid-1500s. Loehle's work thus provides support for the similar finding of higher-than-current temperatures at that time by McIntyre and McKitrick (2003) in their reanalysis of the data employed by Mann *et al*. to create their controversial "hockey stick" temperature history, which gives no indication of the occurrence of this high-temperature regime.

The models developed by Loehle also reveal the existence of three climate cycles previously identified by others. Loehle's seventh model, for example, identifies a 2,388-year cycle he describes as comparing "quite favorably to a cycle variously estimated as 2200, 2300, and 2500 years (Denton and Karlén, 1973; Karlén and Kuylenstierna, 1996; Magny, 1993; Mayewski *et al*., 1997)." There is also a 490-year cycle that likely "corresponds to a 500-year cycle found previously (e.g. Li *et al*., 1997; Magny, 1993; Mayewski *et al*., 1997)" and a 228-year cycle that "approximates the 210-year cycle found by Damon and Jirikowic (1992)."

The compatibility of these findings with those of other studies that have identified solar forcing signals caused Loehle to conclude, "solar forcing (and/or other natural cycles) is plausibly responsible for some portion of 20th century warming."

Other data sets also have provided evidence of a solar influence on temperature. Van Geel *et al.* (1999), for example, reviewed what was known at the time about the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. This analysis indicated "there is mounting evidence suggesting that the variation in solar activity is a cause for millennial scale climate change," which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth's orbit about the Sun. They also reviewed the evidence for mechanisms by which the solar-climate connection might be implemented, concluding "the climate system is far more sensitive to small variations in solar activity than generally believed" and "it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation."

For the period 1856 to 2002, Scafetta and West (2003) compared the form of statistical fluctuations in the intermittency of solar flare activity with the form of statistical fluctuations in Earth's near-surface air temperature as expressed as anomalies relative to the 1961–1990 mean. Both parameters studied were shown to possess time series properties characteristic of dynamical stochastic processes bearing imprints of a particular form of variability called a Levy-walk. The authors report "the affinity of the scaling exponents obtained through our analysis suggests that the Earth's temperature anomalies inherit a Levy-walk memory component from the intermittency of solar flares," which in turn suggests Earth's near-surface air temperature fluctuations arise from variations in solar flare activity.

Scafetta and West found the best correspondence to solar flare variability was obtained for ocean, as opposed to land, temperatures. The oceans, due to their much greater compositional homogeneity and higher heat capacity, would be expected to mirror solar activity better than land masses do. It is also important to note the authors' analysis dealt with short timescales, ranging from weeks to months. Over timescales of tens to hundreds of years, they note, correlations between solar activity and temperature have been well established. The shorter timescale correlation they discovered implies a stronger physical connection between Earth's climate and solar activity than most scientists had previously thought likely. This finding, in the words of Schewe *et al.* (2003), "suggests that for the large part, variations in global temperatures are beyond our control and are instead at the mercy of the Sun's activity."

The 16 authors of Mayewski *et al.* (2004) examined 50 globally distributed paleoclimate records in search of evidence for what they call rapid climate change (RCC) over the Holocene. This terminology is not to be confused with the rapid climate changes typical of glacial periods but is used in place of what the authors call the "more geographically or temporally restrictive terminology such as 'Little Ice Age' and 'Medieval Warm Period.'" RCC events, as they also call them, are multi-century periods of time characterized by extremes of thermal and/or hydrological properties, rather than the much shorter periods of time during which the changes that led to these situations took place.

Mayewski *et al.* identify six RCCs during the Holocene: 9,000–8,000, 6,000–5,000, 4,200–3,800, 3,500–2,500, 1,200–1,000, and 600–150 cal yr BP, the last two of which intervals are the "globally distributed" Medieval Warm Period and Little Ice Age, respectively. With respect to these two periods, they write "the short-lived 1200–1000 cal yr BP RCC event coincided with the drought-related collapse of Maya civilization and was accompanied by a loss of several million lives (Hodell *et al.*, 2001; Gill, 2000), while the collapse of Greenland's Norse colonies at ~600 cal yr BP (Buckland *et al.*, 1995) coincides with a period of polar cooling."

The international team of scientists writes, "of all the potential climate forcing mechanisms, solar variability superimposed on long-term changes in insolation (Bond *et al.*, 2001; Denton and Karlén, 1973; Mayewski *et al.*, 1997; O'Brien *et al.*, 1995) seems to be the most likely important forcing mechanism." They also note "negligible forcing roles are played by CH_4 and CO_2" and "changes in the concentrations of CO_2 and CH_4 appear to have been more the result than the cause of the RCCs."

Raspopov *et al.* (2008), a team of eight researchers from China, Finland, Russia, and Switzerland, describe evidence making the case for a causative link, or set of links, between solar forcing and climate change.

Working with tree-ring width data obtained from two types of juniper found in Central Asia—

Juniperus turkestanica (related to variations in summer temperature in the Tien Shan Mountains) and *Sabina przewalskii* (related to variations in precipitation on the Qinghai-Tibetan Plateau)—Raspopov *et al*. employed band-pass filtering in the 180- to 230-year period range, wavelet transformation (Morlet basis) for the range of periods between 100 and 300 years, and spectral analysis in order to compare the variability in the two tree-ring records with independent $\Delta^{14}C$ variations representative of the approximate 210-year de Vries solar cycle over the past millennium. They found the approximate 200-year cyclical variations present in the palaeoclimatic reconstructions were well correlated (R^2 = 0.58-0.94) with similar variations in the $\Delta^{14}C$ data, suggesting the existence of a solar-climate connection. In addition, they say "the de Vries cycle has been found to occur not only during the last millennia but also in earlier epochs, up to hundreds of millions [of] years ago."

After reviewing additional sets of published palaeoclimatic data from various parts of the world, the eight researchers concluded the same periodicity is evident in Europe, North and South America, Asia, Tasmania, Antarctica, and the Arctic, as well as "sediments in the seas and oceans," citing 20 independent research papers in support of this statement. They conclude there is "a pronounced influence of solar activity on global climatic processes" related to "temperature, precipitation and atmospheric and oceanic circulation."

Raspopov *et al*. also report there can sometimes be "an appreciable delay in the climate response to the solar signal," as long as 150 years, and they note regional climate responses to the de Vries cycle "can markedly differ in phase," even at distances of only hundreds of kilometers, because of "the nonlinear character of the atmosphere-ocean system response to solar forcing." Nevertheless, their work testifies to the validity of their primary conclusion, that throughout the past millennium and stretching back in time as much as 250 million years, the de Vries cycle has been "one of the most intense solar activity periodicities that affected climatic processes." As for the more recent historical significance of the de Vries cycle, Raspopov *et al*. write "the temporal synchrony between the Maunder, Sporer, and Wolf minima and the expansion of Alpine glaciers (Haeberlie and Holzhauser, 2003) further points to a climate response to the deep solar minima."

Wanner *et al*. (2008)—18 climate scientists from 13 research institutions in Switzerland, Germany, the United Kingdom, Belgium, and Russia—developed "a general framework for understanding climate changes during the last 6000 years." They analyzed several hundred papers and concluded, among other things, "at decadal to multi-century timescales, climate variability shows a complex picture with indications of a possible role for (i) rapid changes of the natural forcing factors such as solar activity fluctuations and/or large tropical volcanic eruptions, (ii) internal variability including ENSO [El Niño Southern Oscillation] and NAO [North Atlantic Oscillation], (iii) changes of the thermohaline circulation, and (iv) complex feedback mechanisms between ocean, atmosphere, sea ice and vegetation."

Wanner *et al*. also report "notable swings occurred between warm and cold periods, especially the hemispheric-scale warming leading into the Medieval Warm Period and subsequent cooling into the Little Ice Age," the latter of which periods they say "appears at least to be a hemispheric phenomenon." They also note model simulations support the inference that the Little Ice Age "may have been brought about by the coincidence of low Northern Hemisphere orbital forcing during the Late Holocene with unusually low solar activity and a high number of major volcanic events."

de Jager and Duhau (2009) note "solar activity is regulated by the solar dynamo," "the dynamo is a non-linear interplay between the equatorial and polar magnetic field components," and "so far, in Sun-climate studies, only the equatorial component has been considered as a possible driver of tropospheric temperature variations." Thus they set out to examine the neglected polar field's possible influence on global temperature.

Based on "direct observations of proxy data for the two main solar magnetic field components since 1844," de Jager and Duhau derived "an empirical relation between tropospheric temperature variation and those of the solar equatorial and polar activities." When the two researchers applied this relationship to the period 1610–1995, they found a rising linear association for temperature vs. time, upon which were superimposed "some quasi-regular episodes of residual temperature increases and decreases, with semi-amplitudes up to ~0.3°C," and they note "the present period of global warming is one of them."

de Jager and Duhau conclude, "the amplitude of the present period of global warming does not significantly differ from the other episodes of relative warming that occurred in earlier centuries." The late twentieth century episode of relative warming is merely "superimposed on a relatively higher level of solar activity than the others," giving it the appearance of being unique when it isn't.

Mazzarella (2008) analyzed historical series of solar wind turbulence, atmospheric circulation, the rotation of Earth (length of day, LOD), and sea surface temperature, finding an impressive correlation of R=-0.97 between the aa index and zonal pressure (ZI), when aa was shifted ahead five years. Between ZI and LOD the correlation was R=-0.87 with a lag of six years, while the correlation between LOD and SST was R=-0.97 with a lag of four years. Such relationships suggest an increase in solar wind speed causes a decrease in zonal atmospheric circulation after five years, which causes a deceleration of Earth's rotation after four years, which ultimately causes a decrease in sea surface temperature after four years. A 60-year cycle in LOD was identified previously by Mazzarella (2007) at a confidence level greater than 99 percent. If the observed past correlation between LOD and SST continues in the future, the identified 60-year cycle hints toward a possible decline in SST starting in 2005. Recent data seem to support such a result.

Qian and Lu (2010) point out, "to understand the causes of 20th century global warming, the contributions of natural variability and human activities need to be determined," adding "to make sound predictions for this century's climate, understanding past climate change is important." They began with the reconstructed global-mean temperature anomaly history of Mann *et al*. (2008), combined with HadCRUT3 data for 1000–2008, relative to 1961–1990 (Brohan *et al*., 2006). After removing the mean temperatures of the Medieval Warm Period (MWP), Little Ice Age (LIA), and what they denoted the Global Warming Period (GWP), they used a wavelet transform procedure to identify four oscillations in the millennial temperature time series with periods of 21.1, 62.5, 116.0, and 194.6 years.

Next, they examined a reconstructed 400-year solar radiation series based on ^{10}Be data (Lean *et al*., 1995; Bard and Frank, 2006), using the results they obtained "to analyze their causality relationship" with the periodic oscillations they had detected in the reconstructed millennial global-mean temperature series. The two Chinese researchers thus determined "the ~21-year, ~115-year and ~200-year periodic oscillations in global-mean temperature are forced by and lag behind solar radiation variability," and the "relative warm spells in the 1940s and the beginning of the 21st century resulted from overlapping of warm phases in the ~21-year and other oscillations." They note "between 1994 and 2002 all four periodic oscillations reached their peaks and resulted in a uniquely warm decadal period during the last 1000 years," representing the approximate temporal differential between the current Global Warming Period and the prior Medieval Warm Period.

It is important to note Qian and Lu did not need greenhouse gas emissions data to reconstruct the past thousand-year history of Earth's global mean temperature; it was sufficient merely to employ known oscillations in solar radiation variability. The two authors write, "global-mean temperature will decline to a renewed cooling period in the 2030s, and then rise to a new high-temperature period in the 2060s." Given the cessation in warming observed in the surface and lower tropospheric temperature records over the past decade, it appears their prediction is well on its way to being validated.

It is becoming increasingly clear that the millennial-scale oscillation of climate throughout the Holocene is the result of similar-scale oscillations in some aspect of solar activity. As Mayewski *et al.* (2004) suggested a decade ago, "significantly more research into the potential role of solar variability is warranted, involving new assessments of potential transmission mechanisms to induce climate change and potential enhancement of natural feedbacks that may amplify the relatively weak forcing related to fluctuations in solar output."

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3.3.2 Northern Hemisphere

Evidence of the influence of the Sun on Northern Hemisphere temperatures can be found in the research of Bond *et al*. (2001), who examined ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides (^{10}Be and ^{14}C) sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C). This study is described in depth in Section 3.2 of this chapter.

Bond *et al*. found "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum" and "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the solar inferno are experienced throughout the world. Bond *et al*. also observed the oscillations in drift-ice they studied "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system."

Björck *et al*. (2001) assembled a wide range of lacustrine, tree-ring, ice-core, and marine records that reveal a Northern Hemispheric and possibly global cooling event of less than 200 years' duration with a 50-year cooling-peak centered at approximately 10,300 years BP. According to the authors, the onset of the cooling event broadly coincided with rising ^{10}Be fluxes, indicative of decreased solar or geomagnetic forcing; and because "no large magnetic field variation that could have caused this event has been found," the authors postulate "the ^{10}Be maximum was caused by distinctly reduced solar forcing." They also note the onset of the Younger Dryas is coeval with a rise in ^{10}Be flux, as is the Preboreal climatic oscillation.

Pang and Yau (2002) assembled and analyzed a vast amount of data pertaining to phenomena that have been linked reliably to variations in solar activity, including frequencies of sunspot and aurora sightings, the abundance of carbon-14 in the rings of long-lived trees, and the amount of beryllium-10 in the annual ice layers of polar ice cores. For their analysis of sunspot sightings, the authors used a catalogue of 235 Chinese, Korean, and Japanese records compiled by Yau (1988), a catalogue of 270 Chinese records compiled by Zhuang and Wang (1988), a time chart of 139 records developed by Clark and Stephenson (1979), and several later catalogues that made the overall record more complete.

Over the past 1,800 years, the authors identified "some nine cycles of solar brightness change," including the well-known Oort, Wolf, Sporer, Maunder, and Dalton Minima. With respect to the

Maunder Minimum—which occurred between 1645 and 1715 and is widely acknowledged to have been responsible for some of the coldest weather of the Little Ice Age—they report the temperatures of that period "were about one-half of a degree Celsius lower than the mean for the 1970s, consistent with the decrease in the decadal average solar irradiance." The Dalton Minimum occurred roughly between 1799 and 1820, with another dip in Northern Hemispheric temperatures. Since then, the authors state, "the Sun has gradually brightened" and "we are now in the Modern Maximum," which is likely responsible for the warmth of the Current Warm Period.

Although the long-term variations in solar brightness Pang and Yau identified "account for less than 1% of the total irradiance, there is clear evidence that they affect the Earth's climate." The authors' plot of total solar irradiance and Northern Hemispheric temperature from 1620 to the present (their Fig. 1c) indicates the former parameter (when appropriately scaled but without reference to any specific climate-change mechanism) can account for essentially all of the net change experienced by the latter parameter up to about 1980. After that time, the IPCC surface air temperature record rises dramatically, although radiosonde and satellite temperature histories largely match what would be predicted from the solar irradiance record. These facts could be interpreted as new evidence of the inaccuracy of the IPCC temperature history.

Rohling *et al*. (2003) "narrow down" temporal constraints on the millennial-scale variability of climate evident in ice-core $\delta^{18}O$ records by "determining statistically significant anomalies in the major ion series of the GISP2 ice core," after which they conduct "a process-oriented synthesis of proxy records from the Northern Hemisphere." With respect to the temporal relationships among various millennial-scale oscillations in Northern Hemispheric proxy climate records, the authors conclude a "compelling case" can be made for their being virtually in-phase, based on "the high degree of similarity in event sequences and structures over a very wide spatial domain," and "the fact that our process-oriented synthesis highlights a consistent common theme of relative dominance shifts between winter-type and summer-type conditions, ranging all the way across the Northern Hemisphere from polar into monsoonal latitudes." These findings, they additionally note, "corroborate the in-phase relationship between climate variabilities in the high northern latitudes and the tropics suggested in Blunier *et al*. (1998) and Brook *et al*. (1999)."

Although individual cycles of the persistent climatic oscillation "appear to have different intensities and durations," Rohling *et al.* further note, "a mean periodicity appears around ~1500 years (Mayewski *et al*., 1997; Van Kreveld *et al*., 2000; Alley *et al*., 2001)." They further report "this cycle seems independent from the global glaciation state (Mayewski *et al*., 1997; Bond *et al*., 1999)," and "^{10}Be and delta ^{14}C records may imply a link with solar variability (Mayewski *et al*., 1997; Bond *et al*., 2001)."

Usoskin *et al*. (2003) point out "sunspots lie at the heart of solar active regions and trace the emergence of large-scale magnetic flux, which is responsible for the various phenomena of solar activity" that may influence Earth's climate. They also state, "the sunspot number (SN) series represents the longest running direct record of solar activity, with reliable observations starting in 1610, soon after the invention of the telescope." The authors compared SN data with the millennial-scale temperature reconstruction of Mann *et al*. (1999) by extending the directly measured SN record back in time to AD 850 using records of ^{10}Be cosmonuclide concentration derived from polar ice cores. In doing so, they employed detailed physical models "developed for each individual link in the chain connecting the SN with the cosmogenic isotopes," and they combined these models in such a way that "the output of one model [became] the input for the next step."

The resulting reconstructed SN history of the past millennium behaved very much like the infamous "hockey stick" temperature history of Mann *et al*. (1999). It slowly declined over the entire time period—with numerous modest oscillations associated with well-known solar maxima and minima—until the end of the Little Ice Age, whereupon it rose dramatically. Usoskin *et al*. report, for example, "while the average value of the reconstructed SN between 850 and 1900 is about 30, it reaches values of 60 since 1900 and 76 since 1944." In addition, they report "the largest 100-year average of the reconstructed SN prior to 1900 is 44, which occurs in 1140–1240, i.e., during the medieval maximum," but they note "even this is significantly less than the level reached in the last century." Thus they conclude "the high level of solar activity since the 1940s is unique since the year 850."

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3.3.3 North America

Wiles *et al*. (2004) derived a composite Glacier Expansion Index (GEI) for Alaska based on "dendrochronologically derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens," after which they compared this history of glacial activity with "the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability" and the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

The researchers found Alaska ice expansions "approximately every 200 years, compatible with a solar mode of variability," specifically, the de Vries 208-year solar cycle; by merging this cycle with the cyclical behavior of the PDO, Wiles *et al*. obtained a dual-parameter forcing function even better correlated with the Alaskan composite GEI, with major glacial advances clearly associated with the Sporer, Maunder, and Dalton solar minima.

Wiles *et al*. note "increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries." They make no mention of possible CO_2-induced global warming in discussing their results; Alaskan glacial activity "has been shown to be primarily a record of summer temperature change (Barclay *et al*., 1999)" and appears to be sufficiently well explained by solar and PDO variability alone. Four years later, Wiles *et al*. (2008) reconfirmed this solar-climate link in Alaska.

Regarding the nearby Columbia Icefield area of the Canadian Rockies, Luckman and Wilson (2005) used new tree-ring data to update a millennial temperature reconstruction for this region published in 1997. Their update employed different standardization techniques, such as the regional curve standardization method, in an effort to capture a greater degree of low frequency variability (centennial to millennial scale) than reported in the initial study. The new data set added more than one hundred years to the chronology and now covers the period AD 950–1994.

The updated proxy indicator of temperature showed considerable decadal- and centennial-scale variability, where generally warmer conditions prevailed during the eleventh and twelfth centuries, during approximately AD 1350–1450, and from about 1875 through the end of the record. Persistent cold conditions prevailed in 1200–1350, 1450–1550, and 1650–1850, with the 1690s being exceptionally cold (more than 0.4°C colder than the other intervals).

According to Luckman and Wilson, the Columbia Icefield reconstruction "appears to indicate a reasonable response of local trees to large-scale forcing of climates, with reconstructed cool conditions comparing well with periods of known low solar activity," which suggests the Sun is the main driver of these low frequency temperature trends.

Barron and Bukry (2007) extracted sediment cores from three sites on the eastern slope of the Gulf of California and, by examining these high-resolution records of diatoms and silicoflagellate assemblages, reconstructed sea surface temperatures there over the past 2,000 years. In all three of the sediment cores, the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures) was found to be greater during the Medieval Warm Period than at any other time over the 2,000-year period studied. During the Current Warm Period the diatom's relative abundance was lower than the 2,000-year mean, also in all three of the sediment cores. In addition, the first of the cores exhibited elevated *A. nodulifera* abundances from the start of the record to about AD 350, during the latter part of the Roman Warm Period, as well as between AD 1520 and 1560.

By analyzing radiocarbon production data, Barron and Bukry determined "intervals of increased radiocarbon production (sunspot minima) correlate with intervals of enhanced biosilica productivity," leading the two authors to conclude "solar forcing played a major role in determining surface water conditions in the Gulf of California during the past 2000 yr." They note "reduced solar irradiance (sunspot minima) causes cooling of winter atmospheric temperatures above the southwest US" and "this strengthens the atmospheric low and leads to intensification of northwest winds blowing down the Gulf, resulting in increased overturn of surface waters, increased productivity, and cooler SST."

Nederbragt and Thurow (2005) examined a high resolution marine sediment core taken from the Santa Barbara Basin (SBB) to determine whether millennial-scale climate cycles observed in the Atlantic Ocean were also present in the Pacific Ocean. Cross-spectral analyses revealed the presence of two dominant millennial-scale cycles in both the North Atlantic and Pacific SBB sedimentary records at frequencies of ~1000 and 2750 years. They also demonstrated these frequencies are similar to frequencies derived from a record of atmospheric Delta^{14}C typically used as an indicator of solar activity. The coherence between the North Atlantic, Pacific SBB, and atmospheric Delta^{14}C records strongly suggests, in the words of the authors, that "part of the climate variability during the Holocene is the result of variation in solar irradiance as an external forcing mechanism."

Richey *et al.* (2007) constructed "a continuous decadal-scale resolution record of climate variability over the past 1400 years in the northern Gulf of Mexico" from a box core recovered in the Pigmy Basin, northern Gulf of Mexico [27°11.61'N, 91°24.54'W], based on "paired analyses of Mg/Ca and δ^{18}O in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages." They report "two multi-decadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm or warmer than near-modern conditions between 1000 and 1400 yr B.P.," while "foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was 2–2.5°C below modern SST." In addition, they found "four minima in the Mg/Ca record between 900 and 250 yr. B.P. correspond with the Maunder, Sporer, Wolf, and Oort sunspot minima," providing additional evidence the historic warmth of Earth's past was likely solar-induced.

Poore *et al*. (2003) developed a 14,000-year record of Holocene climate based primarily on the relative abundance of the planktic foraminifer *Globigerinoides sacculifer* found in two sediment cores. In reference to North Atlantic millennial-scale cool events 1–7 identified by Bond *et al*. (2001) as belonging to a pervasive climatic oscillation with a period of approximately 1,500 years, Poore *et al*. report distinct excursions to lower abundances of *G. sacculifer* "match within 200 years the ages of Bond events 1–6," noting "major cooling events detected in the subpolar North Atlantic can be recognized in the GOM record." They additionally note "the GOM record includes more cycles than can be explained by a quasiperiodic 1500-year cycle," but such centennial-scale cycles with periods ranging from 200 to 500 years are also observed in the study of Bond *et al*. They note further their results "are in agreement with a number of studies indicating the presence of substantial century-scale variability in Holocene climate records from different areas," specifically citing the reports of Campbell *et al*. (1998), Peterson *et al*. (1991), and Hodell *et al*. (2001). They also discuss evidence that leads them to conclude "some of the high-frequency variation (century scale) in *G. sacculifer* abundance in our GOM records is forced by solar variability."

Lund and Curry (2004) analyzed a planktonic foraminiferal $\delta^{18}O$ time series obtained from three well-dated sediment cores retrieved from the seabed near the Florida Keys (24.4°N, 83.3°W) covering the past 5,200 years. As they describe it, isotopic data from the three cores "indicate the surface Florida Current was denser (colder, saltier or both) during the Little Ice Age than either the Medieval Warm Period or today" and "when considered with other published results (Keigwin, 1996; deMenocal *et al*., 2000), it is possible that the entire subtropical gyre of the North Atlantic cooled during the Little Ice Age, ... perhaps consistent with the simulated effects of reduced solar irradiance (Rind and Overpeck, 1993; Shindell *et al*., 2001)." In addition, they report "the coherence and phasing of atmospheric ^{14}C production and Florida Current $\delta^{18}O$ during the Late Holocene implies that solar variability may influence Florida Current surface density at frequencies between 1/300 and 1/100 years."

A 2012 study found temperatures along the coast of Cape Hatteras pulsated according to the rhythm of the 1,000-year solar cycle (Cléroux *et al*., 2012). The climate of British Columbia also has been driven by solar activity changes over the past 11,000 years (Gavin *et al*., 2012).

Li *et al*. (2006) "recovered a 14,000-year mineral-magnetic record from White Lake (~41°N, 75°W), a hardwater lake containing organic-rich sediments in northwestern New Jersey, USA." A comparison of the White Lake data with climate records from the North Atlantic sediments "shows that low lake levels at ~1.3, 3.0, 4.4, and 6.1 ka [1000 years before present] in White Lake occurred almost concurrently with the cold events at ~1.5, 3.0, 4.5, and 6.0 ka in the North Atlantic Ocean (Bond *et al*., 2001)" and "these cold events are associated with the 1500-year warm/cold cycles in the North Atlantic during the Holocene" that have "been interpreted to result from solar forcing (Bond *et al*., 2001)."

Long periods of warmth forced by variable solar activity in North America have occurred over and over again throughout the Holocene and beyond (Oppo *et al*., 1998; Raymo *et al*., 1998), suggesting the Current Warm Period also was instigated by this recurring phenomenon, not the CO_2 output of the Industrial Revolution.

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3.3.4 South America

Nordemann *et al*. (2005) examined tree rings from species sensitive to fluctuations in temperature and precipitation throughout the southern region of Brazil and Chile, along with sunspot data, via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding of the effects of solar activity, climate, and geophysical phenomena on the continent of South America, where the time interval covered by the tree-ring samples from Brazil was 200 years and that from Chile was 2,500 years. Results of the spectral analysis revealed periodicities in the tree rings that corresponded well with the DeVries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles, while wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Utilizing a lichenometric method for dating glacial moraines, the Bolivian and French research team of Rabatel *et al*. (2005) developed "the first detailed chronology of glacier fluctuations in a tropical area during the Little Ice Age," focusing on fluctuations of the Charquini glaciers of the Cordillera Real in Bolivia, where they studied a set of 10 moraines that extend below the present glacier termini. The researchers determined the maximum glacier extension in Bolivia "occurred in the second half of the 17th century, as observed in many mountain areas of the Andes and the Northern Hemisphere." In addition, they found "this expansion has been of a comparable magnitude to that observed in the Northern Hemisphere, with the equilibrium line altitude depressed by 100–200 m during the glacier maximum." They say "the synchronization of glacier expansion with the Maunder and Dalton minima supports the idea that solar activity could have cooled enough the tropical atmosphere to provoke this evolution."

As for the magnitude and source of the cooling in the Bolivian Andes during the Little Ice Age, three years later Rabatal *et al*. (2008) estimated it to have been 1.1 to 1.2°C below that of the present, once again noting there was a "striking coincidence between the glacier expansion in this region of the tropics and the decrease in solar irradiance: the so-called 'Maunder minimum' (AD 1645-1715) during which irradiance might have decreased by around 0.24% (Lean and Rind, 1998) and could have resulted in an atmospheric cooling of 1°C worldwide (Rind *et al*., 2004)."

Glasser *et al*. (2004) analyzed a large body of evidence related to glacier fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte (47°00'S, 73°39'W) and the Hielo Patagonico Sur (between 48°50'S and 51°30'S). The glacial advancements that occurred during the cold interval preceding the Roman Warm Period are "part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al*., 1998; Wasson and Claussen, 2002), which coincides with an abrupt decrease in solar activity"; they add this observation "led van Geel *et al*. (2000) to suggest that variations in solar irradiance are more important as a driving force in variations in climate than previously believed."

With respect to the most recent recession of Hielo Patagonico Norte outlet glaciers from their late historic moraine limits at the end of the nineteenth century, Glasser *et al*. say "a similar pattern can be observed in other parts of southern Chile (e.g., Kuylenstierna *et al*., 1996; Koch and Kilian, 2001)." They note "in areas peripheral to the North Atlantic and in central Asia the available evidence shows that glaciers underwent significant recession at this time (cf. Grove, 1988; Savoskul, 1997)," which again suggests a globally distributed forcing factor such as cyclically variable solar activity.

Studying a bog, as opposed to a glacier, Chambers *et al*. (2007) presented new proxy climate data obtained from the Valle de Andorra northeast of Ushuaia, Tierra del Fuego, Argentina. These data, they emphasize, are "directly comparable" with similar proxy climate data obtained in numerous studies conducted in European bogs, "as they were produced using identical laboratory methods." Chambers *et al*. say their South American data show "a major climate perturbation at the same time as in northwest Europe," which they describe as "an abrupt climate cooling" that occurred approximately 2,800 years ago. They write, "its timing, nature and apparent global synchronicity lend support to the notion of solar forcing of past climate change, amplified by oceanic circulation."

Noting "rapid, high-magnitude climate changes might be produced within the Holocene by an inferred decline in solar activity (van Geel *et al*., 1998, 2000, 2003; Bond *et al*., 2001; Blaauw *et al*., 2004; Renssen *et al*., 2006)," the five European researchers conclude this "has implications for rapid, high-magnitude climate changes of the opposite direction—climatic warmings, possibly related to increases in solar activity." They further note "for the past 100 years any solar influence would for the most part have been in the opposite direction (i.e., to help generate a global climate warming) to that inferred for c. 2800–2710 cal. BP." They conclude this observation "has implications for interpreting the relative contribution of climate drivers of recent 'global warming.'"

Polissar *et al*. (2006) worked with data derived from sediment records of two Venezuelan watersheds along with ancillary data obtained from other studies conducted in the same general region. They developed continuous decadal-scale histories of glacier activity and moisture balance in a part of the tropical Andes (the Cordillera de Merida) over the past millennium and a half, from which they deduced contemporary histories of regional temperature and precipitation.

The international (Canada, Spain, United States, Venezuela) team of scientists writes, "comparison of the Little Ice Age history of glacier activity with reconstructions of solar and volcanic forcing suggest that solar variability is the primary underlying cause of the glacier fluctuations," because "the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and δ^{14}C measurements"; "spectral analysis shows significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, closely matching the de Vries and Gleissberg oscillations identified from solar irradiance reconstructions"; and "solar and volcanic forcing are uncorrelated between AD 1520 and 1650, and the magnetic susceptibility record follows the solar-irradiance reconstruction during this interval." In addition, they note "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima" and "temperature declines of -3.2 ± 1.4°C and precipitation increases of ~20% are required to produce the observed glacial responses."

Polissar *et al*. say their results "suggest considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability."

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3.3.5 Asia

Bashkirtsev and Mashnich (2003), two scientists from the Institute of Solar-Terrestrial Physics of the Siberian Division of the Russian Academy of Sciences, note in the Russian journal *Geomagnetizm i Aeronomiya*, "a number of publications report that the anthropogenic impact on the Earth's climate is an obvious and proven fact," when in their opinion "none of the investigations dealing with the anthropogenic impact on climate convincingly argues for such an impact."

They cite the work of Friis-Christensen and Lassen (1991), who first noted the close relationship (r = -0.95) between the length of the sunspot cycle and the surface air temperature of the Northern Hemisphere over the period 1861–1989, where "warming and cooling corresponded to short (~10 yr) and prolonged (~11.5 yr) solar cycles, respectively." They also cite the work of Zherebtsov and Kovalenko (2000), who established a high correlation (r = 0.97) between "the average power of the solar activity cycle and the surface air temperature in the Baikal region averaged over the solar cycle." These two findings, Bashkirtsev and Mashnich contend, "leave little room for the anthropogenic impact on the Earth's climate." In addition, they note "solar variations naturally explain global cooling observed in 1950–1970, which cannot be understood from the standpoint of the greenhouse effect, since CO_2 was intensely released into the atmosphere in this period," citing the work of Dergachev and Raspopov (2000).

Bashkirtsev and Mashnich conduct wavelet-spectra and correlation analyses of Irkutsk and world air temperatures and Wolf number data for the period 1882–2000, finding periodicities of 22 (Hale cycle) and 52 (Fritz cycle) years and reporting "the temperature response of the air lags behind the sunspot cycles by approximately 3 years in Irkutsk and by 2 years over the entire globe."

Noting one could thus expect the upper envelope of sunspot cycles to reproduce the global temperature trend, they created such a plot and found "the lowest temperatures in the early 1900s correspond to the lowest solar activity (weak cycle 14), the further temperature rise follows the increase in solar activity; the decrease in solar activity in cycle 20 is accompanied by the temperature fall [from 1950–1970], and the subsequent growth of solar activity in cycles 21 and 22 entails the temperature rise [of the past quarter century]."

Bashkirtsev and Mashnich conclude "it has become clear that the current sunspot cycle (cycle 23) is weaker than the preceding cycles (21 and 22)" and "solar activity during the subsequent cycles (24 and 25) will be, as expected, even lower," noting "according to Chistyakov (1996, 2000), the minimum of the secular cycle of solar activity will fall on cycle 25 (2021–2026), which will result in the minimum global temperature of the surface air (according to our prediction)."

Vaganov *et al*. (2000) utilized tree-ring width as a proxy for temperature to examine temperature variations in Asia over the past 600 years. According to a graph of the authors' data, temperatures in the Asian subarctic exhibited a small positive trend from the start of the record until about 1750. Thereafter, a severe cooling trend ensued, followed by a 130-year warming trend from about 1820 through 1950, after which temperatures fell once again. The authors state the amplitude of twentieth century warming "does not go beyond the limits of reconstructed natural temperature fluctuations in the Holocene subarctic zone." They also report finding a significant correlation with solar radiation and volcanic activity over the entire 600-year period (R = 0.32 for solar radiation, R = -0.41 for volcanic activity), and this correlation actually improved over the shorter interval of the industrial period, 1800 to 1990 (R = 0.68 for solar radiation, R = -0.59 for volcanic activity).

In this region of the world, where climate models predict large increases in temperature as a result of the historical rise in the air's CO_2 concentration, real-world data show a cooling trend since around 1940, when the greenhouse effect of CO_2 should have been most prevalent. Where warming does exist in the record (between about 1820 and 1940), much of it correlates with changes in solar irradiance and volcanic activity—two factors free of anthropogenic influence.

In two additional paleoclimate studies from the continental interior of Russia's Siberia, Kalugin *et al*. (2005) and Kalugin *et al*. (2007) analyzed sediment cores from Lake Teletskoye in the Altai Mountains (51°42.90'N, 87°39.50'E) to produce multi-proxy climate records spanning the past 800 years. Analyses of the multi-proxy records revealed several distinct climatic periods over the past eight centuries. The regional climate was relatively warm, with high terrestrial productivity, from AD 1210 to 1380. Thereafter, temperatures cooled, reaching peak deterioration between 1660 and 1700, which, in the words of Kalugin *et al*. (2005), "corresponds to the age range of the well-known Maunder Minimum (1645–1715)" of solar sunspot activity.

Aono and Kazui (2008) developed an uninterrupted 1,100-year history of March mean temperature at Kyoto, Japan using phenological data on the times of full-flowering of cherry trees (*Prunus jamasakura*) acquired from old diaries and chronicles written at Kyoto. That record was reconciled with instrumental temperature measurements obtained over the period 1881–2005 and compared with the sunspot number history developed by Solanki *et al*. (2004).

The researchers report "the existence of four cold periods, 1330–1350, 1520–1550, 1670–1700, and 1825–1830, during which periods the estimated March mean temperature was 4–5°C, about 3–4°C lower than the present normal temperature," and "these cold periods coincided with the less extreme periods [of solar activity], known as the Wolf, Spoerer, Maunder, and Dalton minima, in the long-term solar variation cycle, which has a periodicity of 150–250 years." In addition, they report "a time lag of about 15 years was detected in the climatic temperature response to short-term solar variation."

Kitagawa and Matsumoto (1995) analyzed $\delta^{13}C$ variations of Japanese cedars growing on Yakushima Island (30°20'N, 130°30'E) in an effort to reconstruct a high-resolution proxy temperature record over the past two thousand years. In addition, they applied spectral analysis to the $\delta^{13}C$ time series in an effort to learn if any significant periodicities were present in the record. They found significant decadal to centennial-scale variability throughout the record, with temperatures fluctuating by about 5°C across the series. Between AD 700–1200 they found a 1°C rise in average temperature (pre-1850 average), which the authors state "appears to be related to the 'Medieval Warm Period.'" By contrast, temperatures were about 2°C below the long-term pre-1850 average during the multi-century Little Ice Age between AD 1580 and 1700. Kitagawa and Matsumoto also report finding significant temperature periodicities of 187, 89, 70, 55, and 44 years. Noting the 187-year cycle closely corresponds to the well-known Suess cycle of solar activity and the 89-year cycle compares well with the Gleissberg solar cycle, they conclude their findings provide further support for a Sun-climate relationship.

Ten years later, Cini Castagnoli *et al*. (2005) reexamined the Kitagawa and Matsumoto data set for evidence of recurring cycles using Singular Spectrum Analysis and Wavelet Transform, after which it was compared with a 300-year record of sunspots. Their analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity plus a second multi-decadal oscillation of about 87 years for the tree-ring series in phase with the amplitude modulation of the sunspot number series over the past 300 years. They concluded the overall phase agreement between the climate reconstruction and variation in the sunspot number series "favors the hypothesis that the [multi-decadal] oscillation" revealed in the record "is connected to the solar activity."

Several studies have documented a solar influence on temperature in China from several proxy temperature indicators. Paulsen *et al*. (2003) utilized high-resolution records of $\delta^{13}C$ and $\delta^{18}O$ from a stalagmite in Buddha Cave, central China [33°40'N, 109°05'E], to infer changes in climate over the past 1,270 years. Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." The data also revealed a number of other cycles superimposed on these major millennial-scale temperature cycles, which they attributed to cyclical solar and lunar phenomena.

Tan *et al*. (2004) established an annual layer thickness chronology for a stalagmite from Beijing Shihua Cave and reconstructed a 2,650-year (BC 665–AD 1985) warm season (MJJA: May, June, July, August) temperature record for Beijing by calibrating the thickness chronology with the observed MJJA temperature record (Tan *et al*., 2003). The warm season temperature record was "consistent with oscillations in total solar irradiance inferred from cosmogenic ^{10}Be and ^{14}C" and "remarkably consistent with Northern Atlantic drift ice cycles that were identified to be controlled by the Sun through the entire Holocene [Bond *et al*., 2001]." Both records clearly depict the start of the Current Warm Period, Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, Roman Warm Period, and the cold climate at the start of both records.

The authors conclude "the synchronism between the two independent Sun-linked climate records therefore suggests that the Sun may directly couple hemispherical climate changes on centennial to millennial scales." The cyclical nature of the millennial-scale oscillation of climate evident in both climate records suggests there is no need to invoke rising atmospheric CO_2 concentrations as a cause of the Current Warm Period.

Working with a stalagmite found in Wanxiang Cave (33°19'N, 105°00'E), Zhang *et al*. (2008) developed a $\delta^{18}O$ record with an average resolution of 2.5 years covering the period AD 190 to 2003. According to the 17 authors, the $\delta^{18}O$ record "exhibits a series of centennial to multi-centennial fluctuations broadly similar to those documented in Northern Hemisphere temperature reconstructions, including the Current Warm Period, Little Ice Age, Medieval Warm Period and Dark Age Cold Period."

In addition, Zhang *et al*. state the $\delta^{18}O$ record "correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes." In a commentary that accompanied Zhang *et al*.'s article, Kerr (2008) quotes other researchers calling the Zhang *et al*. record "amazing," "fabulous," and "phenomenal," noting it "provides the strongest evidence yet for a link among Sun, climate, and culture."

A team led by Professor ZhongHui Liu of Hong Kong University recently reported additional empirical evidence for solar forcing of temperatures around northern Tibetan Plateau, shown in Figure 3.3.5.1 below. The authors (He *et al.*, 2013), writing in *Chinese Science Bulletin*, presented the alkenone-based reconstruction of temperatures, at decadal resolution, from Lake Gahai and Lake Sugan covering about 2,600 and 2,200 years, respectively. The estimated warmth of the MWP period is as much as 1.9°C warmer than the modern warm period. The temperature reconstruction makes clear the close relationship of the warm-cold variations with the changing solar activity levels over the same interval.

Hong *et al*. (2000) developed a 6,000-year high-resolution $\delta^{18}O$ record from plant cellulose deposited in a peat bog in the Jilin Province of China (42° 20' N, 126° 22' E), from which they inferred the temperature history of that location over the past six millennia. They compared this record with a previously derived $\delta^{14}C$ tree-ring record representative of the intensity of solar activity over this period.

The area was found to have been relatively cold between 4000 and 2600 BC, then warming until it reached the maximum warmth of the record in about 1600 BC, after which it fluctuated about this warm mean for approximately 2,000 years. Starting about AD 350, the climate began to cool, with the most dramatic cold associated with three temperature minima centered at about AD 1550, 1650, and 1750, corresponding to the most severe cold of the Little Ice Age.

The authors call attention to their finding of "an obvious warm period represented by the high $\delta^{18}O$ from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe." They also report "at that time, the northern boundary of the cultivation of citrus tree (*Citrus reticulata Blanco*) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, and it has been estimated that the annual mean temperature was 0.9-1.0°C higher than at present." Hong *et al*. also note "there is a remarkable, nearly one to one, correspondence between the changes of atmospheric $\delta^{14}C$ and the variation in $\delta^{18}O$ of the peat cellulose," which led them to conclude the temperature history of the past 6,000 years at the site of their study has been "forced mainly by solar variability."

Porter and Weijian (2006) analyzed 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers "represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation," while "brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate." They also report the climatic variations they discovered "correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water."

The researchers state "the correspondence of these records over the full span of Holocene time implies a close relationship between North Atlantic climate and the monsoon climate of central China." They also note the most recent of the episodic cold periods, which they identify as the Little Ice Age, began about AD 1370, while the preceding cold period ended somewhere in the vicinity of AD 810. Their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. Relating this millennial-scale climate cycle to the similar-scale drift-ice cycle of Bond *et al.* (2001) implies they accept solar forcing as the most likely cause of the alternating multi-century mild/moist and cold/dry periods of North-Central China.

Further evidence of a solar-climate link has been obtained from the Tibetan Plateau in China. Wang *et al*. (2002), for example, studied changes in $\delta^{18}O$ and NO_3^- in an ice core retrieved from the Guliya Ice Cap (35°17'N, 81°29'E), comparing their results with

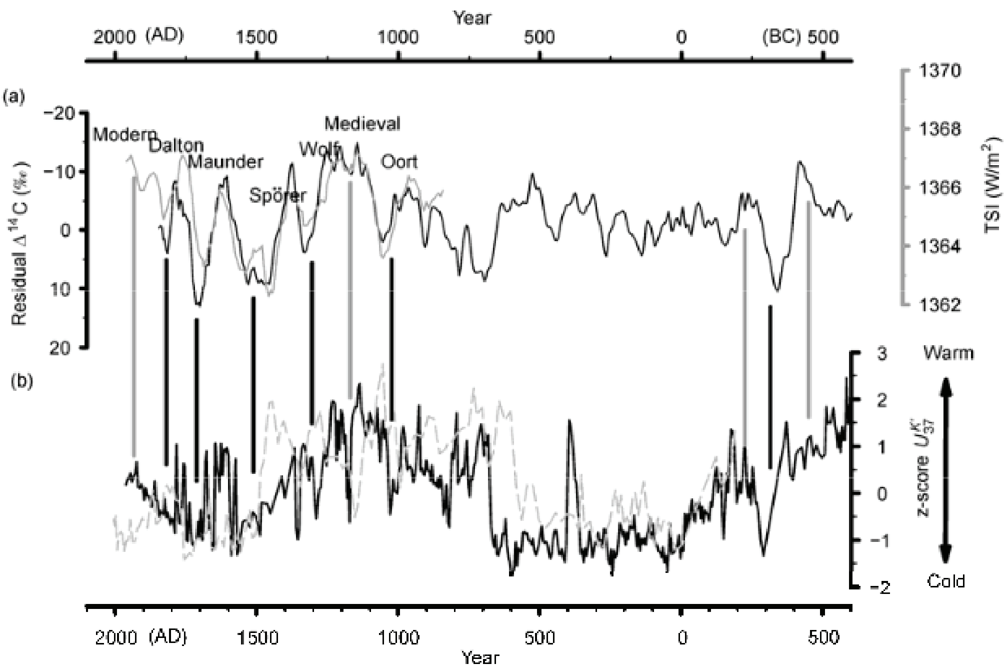

Figure 3.3.5.1. Correlations between solar activity proxies (top curves: TSI-grey; 14C-black) and temperature proxies (bottom curves: Lake Sugan-grey; Lake Gahai-black) from northern Tibetan Plateau. Reprinted with permission from He, Y.X., Liu, W.G., Zhao, C., Wang, Z., Wang, H.Y., Liu, Y., Qin, X.Y., Hu, Q.H., An, Z.S., and Liu, Z.H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

ancillary data from Greenland and Antarctica. Two cold events—a weak one around 9.6–9.2 thousand years ago (ka) and a strong one referred to as the "8.2 ka cold event"—were identified in the Guliya ice core record. The authors report these events occurred "nearly simultaneously with two ice-rafted episodes in the North Atlantic Ocean." They also note both events occurred during periods of weakened solar activity.

Remarking that evidence for the 8.2 ka cold event "occurs in glacial and lacustrine deposits from different areas," the authors say this evidence "suggests that the influence of this cold event may have been global." They also say "comprehensive analyses indicate that the weakening of solar insolation might have been the external cause of the '8.2 ka cold event'" and "the cause of the cold event around 9.6–9.2 ka was also possibly related to the weaker solar activity." The authors thus conclude these observations imply "millennial-scale climatic cyclicity might exist in the Tibetan Plateau as well as in the North Atlantic."

Xu *et al*. (2002) studied plant cellulose $\delta^{18}O$ variations in cores retrieved from peat deposits west of Hongyuan County at the northeastern edge of the Qinghai-Tibetan Plateau (32° 46'N, 102° 30'E). The authors report finding three consistently cold events centered at approximately 500, 700, and 900 AD, during what is sometimes referred to as the Dark Ages Cold Period. Then, for the period 1100–1300 AD, they report "the $\delta^{18}O$ of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the 'Medieval Warm Period.'" Finally, they note "the periods 1370–1400 AD, 1550–1610 AD, [and] 1780–1880 AD recorded three cold events, corresponding to the 'Little Ice Age.'"

Power spectrum analyses of their data revealed periodicities of 79, 88, and 123–127 years, "suggesting that the main driving force of Hongyuan climate change is from solar activities." In a subsequent paper by the same authors, Xu *et al.* (2006) compared the Hongyuan temperature variations with solar activity inferred from atmospheric ^{14}C and ^{10}Be concentrations measured in a South Pole ice core, after which they performed cross-spectral analyses to determine the relationship between temperature and solar variability, comparing their results with similar results obtained by other researchers.

Xu *et al*. (2006) report, "during the past 6000 years, temperature variations in China exhibit high synchrony among different regions, and importantly, are in-phase with those discovered in other regions in the northern hemisphere." They also say their "comparisons between temperature variations and solar activities indicate that both temperature trends on centennial/millennial timescales and climatic events are related to solar variability." The researchers conclude "quasi-100-year fluctuations of solar activity may be the primary driving force of temperature during the past 6000 years in China."

Two years later Tan *et al*. (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau's northeast margin since AD 960 based on an analysis of Chinese historical records, after which they compared the result with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories.

Tan *et al*. discovered "high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere." Consequently, their precipitation record may be used to infer a Medieval Warm Period that stretched from approximately AD 960 to 1230, with temperature peaks in the vicinity of AD 1000 and 1215 that clearly exceeded the twentieth century peak temperature of the Current Warm Period. They also found "good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record." These findings harmonize, in their words, with "numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene," in support of which they attach 22 scientific references.

Tan *et al*. conclude the "synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity," which apparently produced a Medieval Warm Period both longer and stronger than what has been experienced to date during the Current Warm Period in the northeast margin of the Tibetan Plateau.

Xu *et al*. (2008) studied decadal-scale temperature variations of the past six centuries derived from four high-resolution temperature indicators—the $\delta^{18}O$ and $\delta^{13}C$ of bulk carbonate, total carbonate content, and the detrended $\delta^{15}N$ of organic matter—extracted from Lake Qinghai (36°32'-37°15'N, 99°36'-100°47'E) on the northeast Qinghai-Tibet plateau, comparing the resultant variations with proxy temperature indices derived from nearby tree rings and reconstructed solar activity. The analysis revealed "four obvious cold intervals during the past 600 years at Lake Qinghai, namely 1430–1470, 1650–1715, 1770–1820 and 1920–1940," and "these obvious cold intervals are also synchronous with the minimums of the sunspot numbers during the past 600 years," namely, "the Sporer, the Maunder, and the Dalton minimums." These facts strongly suggest, in their words, "that solar activities may dominate temperature variations on decadal scales at the northeastern Qinghai-Tibet plateau."

If the development of the significant cold of the Little Ice Age was driven by a change in some type of solar activity, it logically follows that the global warming of the twentieth century was driven primarily by the reversal of that trend in solar activity, not by the historical rise in the air's CO_2 content. However, as also noted by Xu *et al*., how small perturbations of solar activity have led "to the observed global warming, what is the mechanism behind it, etc., are still open questions."

The authors write, "the middle reach of the Yangtze River possesses abundant depositional resources (e.g. stalagmite, peatland and lake sediments)," which "are reliable information carriers for paleoclimate and paleoenvironmental reconstruction." They add "the reconstruction of long-term paleoclimate change would provide the premise for accurate prediction of the future."

Soon *et al.* (2011) revealed a high degree of correlation between Chinese surface temperature records and two measures of solar radiation: a reconstruction of total solar irradiance (TSI) over the interval 1880–2002 (Figure 3.3.5.2) and a reconstruction of sunshine duration (Figure 3.3.5.3). The correlation between the data sets resembles an earlier correlation published by Soon (2005) between Arctic-wide surface temperature and TSI. Such strong correlations between temperature and solar-related indices from different geographical regions, together with the solar modulation of the Atlantic Meridional overturning circulation on multidecadal to centennial timescales (Soon, 2009), suggest solar forcing at the top of the atmosphere can and does persist to influence or drive climatic change near the surface of Earth. The simultaneous existence of the correlation between Chinese surface temperature with the two different measures of solar radiation may provide a

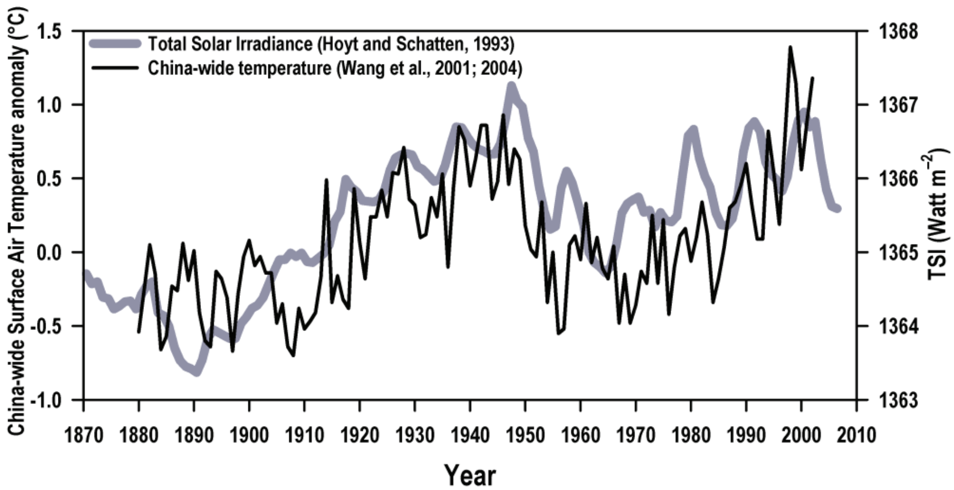

Figure 3.3.5.2. The empirical correlation between China-wide surface air temperature and estimated total solar irradiance from 1880 to 2002. Reprinted with permission from Soon, W., Dutta, K., Legates, D.R., Velasco, V., and Zhang, W. 2011. Variation in surface air temperature of China during the 20th Century. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 2331–2344.

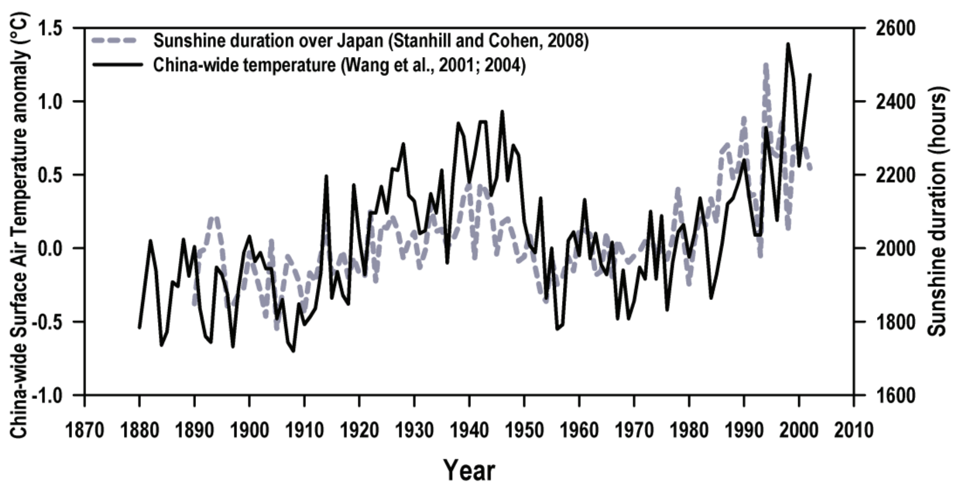

Figure 3.3.5.3. The empirical correlation between China-wide surface air temperature and the Japanese sunshine duration record from Stanhill and Cohen (2008) from 1890 to 2002. Also reprinted with permission from Soon *et al.* 2011.

strong physical constraint on how the Sun's irradiation can systematically modulate surface air temperature, at least in China.

Soon *et al.*'s work also explores the difficult challenge of having to explain how the transparency of the atmospheric column changes over time, through changing cloud fields and/or through more or less loading of particulate matters. According to the authors, the empirical results shown in their two figures reproduced here may be related to a key meteorological phenomenon involving the so-called Asian-African westerly jets, which Soon *et al.* (2011) say provide direct evidence to support a real physical Sun-climate link, as opposed to a mere statistical coincidence. A specific wave-5 or -6 pattern of circumglobal teleconnection among five or six regional centers of action is used to explain why the widely separated meteorological regimes and climatic zones are interconnected.

It is important to point out the enormous difficulties of modeling such empirical observations even using the best computer climate models of our day. It is not an exaggeration to say this one hurdle—not knowing how solar radiation propagates and changes from the top of the atmosphere to the near-surface or surface—has for at least the past 100 years prevented or slowed scientific progress into the Sun-climate connection.

Through phytolith analysis of a sediment core extracted at Zhoulao town in China's Jianli County in AD 2000, Gu *et al*. (2012) reconstructed a high-resolution record of paleoclimate change over the past 15,000 years in the middle reaches of the Yangtze River. They compared their results with paleoclimatic indicators derived from stalagmites, peatlands, North Atlantic deep-sea sediments (Bond *et al*., 1997, 2001), the Loess Plateau of Central China, and Arabic Sea sediments. The five Chinese scientists identified eight climatic phases over the temperature reconstruction: the Last Glacial Maximum (20–14.8 cal ka BP), the Last Deglaciation (14.8–11.9 cal ka BP), a low temperature phase in the Early Holocene (11.9–8 cal ka BP), the Holocene Optimum (8–4.9 cal ka BP), the Holocene Katathermal (4.9–1.1 cal ka BP), the Medieval Warm Period (1.1–0.7 cal ka BP), the Little Ice Age (0.7–0.15 cal ka BP), and the Modern Warming (0.15 cal ka BP-present). In addition, they discovered the climate history of their research area had strong links with the contemporary histories of the Indian Summer Monsoon, the Asian Summer Monsoon, and the Holocene drift-ice events of the North Atlantic Ocean, which were discovered and described by Bond *et al*. (1997, 2001). Gu *et al*. conclude the correlation between their climate history and the Bond events "reveals that solar activity controls the Earth surface climate system at the centennial and millennial scales."

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3.3.6 Europe

Holzhauser *et al*. (2005) presented high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, starting with an in-depth analysis of the Great Aletsch glacier, the largest glacier in the European Alps.

The three researchers report "during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today," noting "the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al*., 2003)." After an intervening unnamed cold-wet phase, during which the glacier grew in both mass and length, they find "during the Iron/Roman Age Optimum between c. 200 BC and AD 50," better known as the Roman Warm Period, the glacier again retreated and "reached today's extent or was even somewhat shorter than today." Their records also identified the Dark Ages Cold Period, followed by "the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300," a cold-wet phase "characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60," after which the glacier began its latest and still-ongoing recession in 1865. Holzhauser *et al*. also note written documents from the fifteenth century AD indicate at some time during that hundred-year interval "the glacier was of a size similar to that of the 1930s."

Data pertaining to the Gorner glacier (the second largest in the Swiss Alps) and Lower Grindelwald glacier of the Bernese Alps tell much the same story, as Holzhauser *et al*. report these glaciers and the Great Aletsch glacier "experienced nearly synchronous advances" throughout the study period. The Swiss and French scientists report "glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity," which in their estimation "suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlén, 1973; Magny, 1993; van Geel *et al*., 1996; Bond *et al*., 2001)." They conclude by stating "a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene."

Hormes *et al*. (2006) determined radiocarbon dates of 71 samples of wood and peat found in the basal shear planes and proglacial outwashes of eight mid-latitude glaciers in the Central Swiss Alps. They found the dates clustered within discrete time intervals and were able to specify periods during which the glaciers' leading edges were less extended than during the 1990s. "The glaciers investigated were less extensive than during the 1990s, with a shorter length during several defined periods," they noted. These defined periods were: 10,110–9,550, 9,210–7,980, 7,450–6,500, 6,370–5,950, 5,860–3,360, 2,940–2,620 and 2,500–1,170 years before present. They also report "some of these periods with reduced glacier lengths are also documented on Svalbard in the Arctic, the Subantarctic Kerguelen islands in the Indian Ocean, and in Scandinavia." They point out "the defined radiocarbon-dated periods with less extensive glaciers coincide well with periods of reduced ^{14}C production, pointing to the Sun's role in glacier variation processes."

Mauquoy *et al*. (2002a) extracted peat monoliths from ombrotrophic mires at Lille Vildmose, Denmark (56°50'N, 10°15'E) and Walton Moss, UK (54°59'N, 02°46'W), sites which, being separated by about 800 km, "offer the possibility of detecting supraregional changes in climate." From these monoliths, vegetative macrofossils were extracted at contiguous 1-cm intervals and examined using light microscopy. Where increases in the abundances of *Sphagnum tenellum* and *Sphagnum cuspidatum* were found, a closely spaced series of ^{14}C AMS-dated samples immediately preceding and following each increase was used to "wiggle-match" date them (van Geel and Mook, 1989), enabling comparison of the climate-induced shifts with the history of ^{14}C production during the Holocene.

The work revealed a climatic deterioration that marked the beginning of a period of inferred cool, wet conditions that correspond fairly closely with the Wolf, Sporer, and Maunder Minima of solar activity, as manifest in contemporary $\delta^{14}C$ data. The authors report "these time intervals correspond to periods of peak cooling in 1000-year Northern Hemisphere climate records," adding to the "increasing body of evidence" that "variations in solar activity may well have been an important factor driving Holocene climate change."

Two years later, Mauquoy *et al*. (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes of climate change during the Holocene. The authors state "analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al*. (1995), van Geel *et al*. (1996), Speranza *et al*. (2000), Speranza (2000) and Mauquoy *et al*. (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977)." This close correspondence suggests "changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al*., 1996, 1998, 1999, 2000) and the 'Little Ice Age' series of palaeoclimatic changes."

Berstad *et al*. (2003) used a marine sediment core retrieved from the southern Norwegian continental margin to reconstruct sea surface temperatures (SSTs) from $\delta^{18}O$ data derived from the remains of the planktonic foraminifera species *Neogloboquadrina pachyderma* (summer temperatures) and *Globigerina bulloides* (spring temperatures). Among other things, the authors' work depicts a clear connection between the cold temperatures of the Little Ice Age and the reduced solar activity of the Maunder and Sporer solar minima, as well as between the warm temperatures of the most recent 70 years and the enhanced solar activity of the Modern solar maximum. The researchers clearly imply a causative connection between the SSTs and solar activity, as is also implied by the recent sunspot number reconstruction of Usoskin *et al*. (2003).

Sejrup *et al*. (2010) used two sediment cores extracted from the seabed of the eastern Norwegian Sea (~64°N, 3°E) to develop a 1,000-year proxy temperature record "based on measurements of $\delta^{18}O$ in *Neogloboquadrina pachyderma* (dextral form), a planktonic foraminifer that calcifies at relatively shallow depths within the Atlantic waters of the eastern Norwegian Sea during late summer," which they compared with the temporal histories of various proxies of solar activity. The authors point out "the proxy record of solar variability from cosmogenic nuclides and telescopic observations of sunspots explains a substantial fraction of reconstructed Northern Hemisphere temperature variability during the pre-Industrial portion of the last millennium, with a simulated range of up to 0.4°C for plausible irradiance scaling and climate sensitivity," citing Crowley (2000) and Ammann *et al*. (2007). They add, "at both the intra- and supra-decadal timescales there appear to be regional responses to solar forcing that are significantly larger than the global or hemisphere-scale response," citing Shindell *et al*. (2001), Woods and Lean (2007), and Tung and Camp (2008).

Sejrup *et al*.'s analysis revealed "the lowest isotope values (highest temperatures) of the last millennium are seen ~1100–1300 A.D., during the Medieval Climate Anomaly, and again after ~1950 A.D." In between these warm intervals were the colder temperatures of the Little Ice Age, when lower temperatures (thermal minima) occurred at the times of the Dalton, Maunder, Sporer and Wolf solar minima, such that the $\delta^{18}O$ proxy record of near-surface water temperature was found to be "robustly and near-synchronously correlated with various proxies of solar variability spanning the last millennium," with decade- to century-scale temperature variability of 1 to 2°C revealing the Sun outshined nearly all other forcings of climate change in this region of Earth over the past millennium.

Haltia-Hovi *et al*. (2007) extracted sediment cores from beneath the 0.7-m-thick ice platform on Lake Lehmilampi (63°37'N, 29°06'E) in North Karelia, eastern Finland, after which they identified and counted the approximately 2,000 annual varves in the cores and measured their individual thicknesses and mineral and organic matter contents. These climate-related data were compared with residual $\Delta^{14}C$ data derived from tree rings, which serve as a proxy for solar activity (Figure 3.3.6.1).

According to Haltia-Hovi *et al*., their "comparison of varve parameters (varve thickness, mineral and organic matter accumulation) and the activity of the Sun, as reflected in residual $\Delta^{14}C$ [data] appears to coincide remarkably well in Lake Lehmilampi during the last 2000 years, suggesting

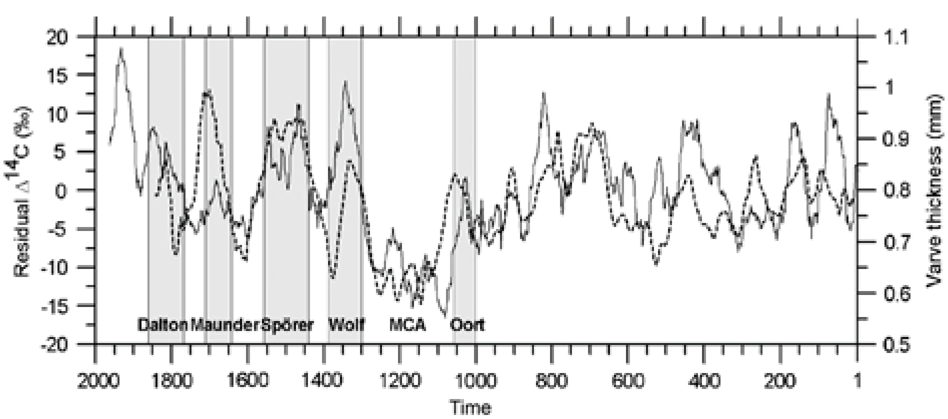

Figure 3.3.6.1. Residual $\Delta^{14}C$ data (dashed line) and varve thickness (smooth line) vs. time, specifically highlighting the Oort, Wolf, Sporer, Maunder and Dalton solar activity minima, as well as the "Medieval Climate Anomaly (also referred to as Medieval Warm Period)," during the contemporaneous "solar activity maxima in the Middle Ages." Reprinted with permission from Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.

solar forcing of the climate," as depicted in the figure below for the case of varve thickness. In addition, the low deposition rate of mineral matter in Lake Lehmilampi in AD 1060–1280 "possibly implies mild winters with a short ice cover period during that time with minor snow accumulation interrupted by thawing periods." They say the low accumulation of organic matter during this period "suggests a long open water season and a high decomposition rate of organic matter." Consequently, since the AD 1060–1280 period shows the lowest levels of both mineral and organic matter content, and since "the thinnest varves of the last 2000 years were deposited during [the] solar activity maxima in the Middle Ages," it is difficult not to conclude that period was likely the warmest of the past two millennia in that part of the world.

Helama *et al*. (2010) examined the Sun-climate relationship in unprecedented detail over the mid- to late-Holocene, beginning a new exploration of Sun-climate co-variations on bimillennial and millennial timescales. They produced a well-dated and annually resolved tree-ring proxy temperature reconstruction from 5500 BCE to 2004 CE representative of the high Arctic region of Northern Lapland, Finland, and Norway (68–70°N, 20–30°E), after which they employed the reconstructed sunspot series for the past 11,000 years developed by Solanki and colleagues in 2004 as a proxy for their solar activity index. Although Helama *et al.* confirmed temperature oscillations on centennial and bicentennial timescales, they focused their study on bimillennial and millennial timescale variations.

Figure 3.3.6.2 shows the band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series are very well correlated if one introduces a time lag of about 70 years. The statistical correlations between the two Sun-climate variables change with time but become more significant during the past 2,000 years with $r = 0.796$ and $p = 0.0066$. The authors were unable to demonstrate similar positive or significant correlations for the Sun-climate variables for bimillennial (band-pass filtering of 1,150 to 3,000 years) scale variations for the past two thousand years (late Holocene), but stronger correlations (with $r = 0.877$ and $p = 0.0121$) were shown to exist between sunspot activity and temperatures at high-latitude Lapland for the Mid Holocene interval at the bimillennial timescale (not shown).

Helama *et al*. suggest the statistical correlations for the Sun and temperature series on millennial timescales depicted in Figure 3.3.6.2 are probably realistic and physically meaningful, especially accounting for a time lag of 60 to 80 years. They posit solar activity may have driven the advection of cold surface waters southward and eastward in the subpolar North Atlantic, and that cold water perturbation may ultimately influence the production of the North Atlantic deep water down to a depth of 2,000 meters. Actions within the high Arctic would take time to propagate further south to affect the formation and working of the North Atlantic Meridional Overturning Circulation; such time lags, although in a shorter range of five to 30 years, have been shown by Eichler *et al*. (2010) and Soon (2009) to be necessary for a physical connection between changes in the Sun and climatic conditions around Europe and North and tropical Atlantic regions.

Helama *et al*. also briefly discuss plausible Sun-climate mechanisms through the atmosphere, invoking changing tropospheric-stratospheric temperature gradients. They ultimately conclude a pathway and mechanism involving the ocean for both memory and redistribution of heat are probably needed to explain what they observed.

Importantly for projections of future climate, Helama *et al*. point out "the near-centennial delay in climate in responding to sunspots indicates that the Sun's influence on climate arising from the current episode of high sunspot numbers [which are the most pronounced of the entire record] may not yet have manifested itself fully in climate trends." They note, "if neglected in climate models, this lag could cause an underestimation of twenty-first-century warming trends."

Hanna *et al*. (2004) analyzed several climatic variables over the past century to determine whether there is "evidence of recent climatic changes" in Iceland. For the period 1923–2002, they found no trend in either annual or monthly sunshine data. Similar results were reported for annual and monthly pressure data, which exhibited semi-decadal oscillations throughout the 1820–2002 period but no significant upward or downward trend. Precipitation, by contrast, appears to have increased slightly, although the authors question the veracity of the trend, citing a number of biases that may have corrupted the database.

With respect to temperature, however, the authors report all stations at the locations they examined for this variable experienced a net warming since the mid-1800s. The warming was not linear over the entire period. Temperatures rose from their coldest

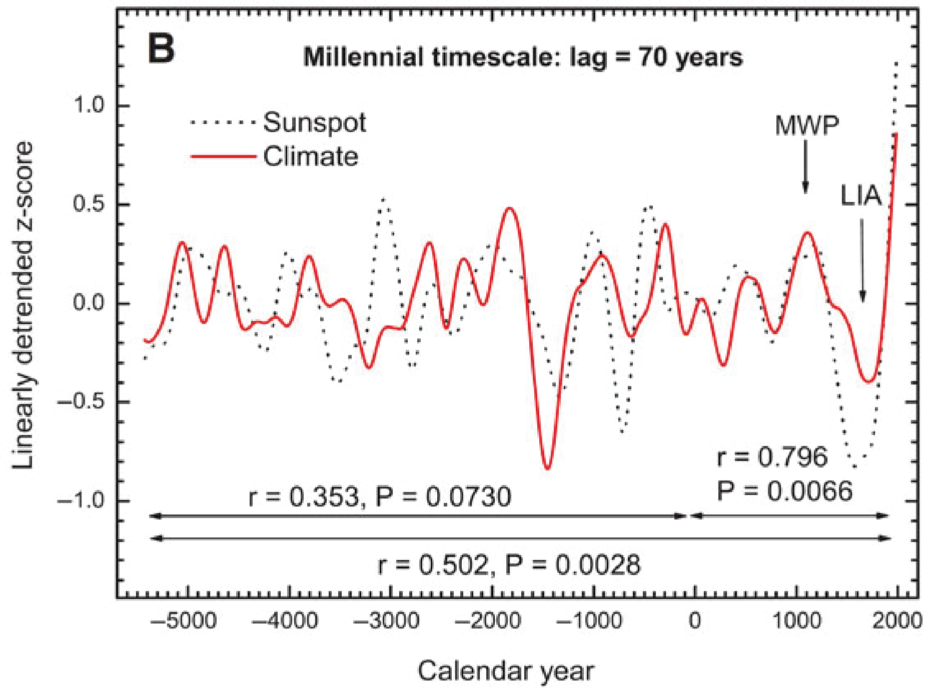

Figure 3.3.6.2. Band-pass filtered (900–1100 years) millennial-scale variations of the sunspot number series and reconstructed tree-ring temperature series lagged by 70 years. Reprinted with permission from Helama, S., Fauria, M.M., Mielikainen, K., Timonen, M., and Eronen, M. 2010. Sub-Milankovitch solar forcing of past climates: Mid and late Holocene perspectives. *Geological Society of America Bulletin* **122**: 1981–1988..

levels in the mid-1800s to their warmest levels in the 1930s, whereupon they remained fairly constant for approximately three decades. Then came a period of rapid cooling, which ultimately gave way to the warming of the 1980s and 1990s. The warming of the past two decades has not resulted in temperatures rising above those observed in the 1930s; the authors state emphatically that "the 1990s was definitely not the warmest decade of the 20th century in Iceland, in contrast to the Northern Hemisphere land average." A linear trend fit to the post-1930 data would indicate an overall temperature decrease since that time.

Hanna *et al*. find a significant correlation between 11-year running temperature means and sunspot numbers, plus the presence of a 12-year peak in their spectral analysis of the pressure data, which they say is "suggestive of solar activity."

Other studies from northern Europe have found similar solar-climate linkages. Temperatures of a Swiss Alpine lake over the past 10,000 years were found to vary with changes in solar activity (Niemann *et al*., 2012). Millennial-scale solar cycles also were found to be responsible for Alpine glacier movement (Nussbaumer *et al*., 2011). Similar cycles also were found in Finnish Lapland. Interestingly, each successive warm phase over the past 2,500 years has been colder than the previous (Esper *et al*., 2012), marking a long-term cooling hardly compatible with the looming climate catastrophe alleged by the IPCC.

Norwegian studies have revealed a significant part of the warming there has been caused by the Sun (Solheim *et al*., 2011; 2012; Humlum *et al*., 2011; Vorren *et al*., 2012). Climate and solar activity also are tightly coupled in Sweden (Kokfelt and Muscheler, 2012). In Finland, evidence of solar cycles has been discovered in tree rings (Ogurtsov *et al*., 2011). Baltic Sea ice extent is known to be influenced by solar activity (Leal-Silva and Velasco Herrera, 2012), as is the ice on the Rhine River in Central Europe (Sirocko *et al*., 2012). A massive cold period in Central Europe 2,800 years ago appears to have been triggered by a weak Sun (Martin-Puertas *et al*., 2012). The North Atlantic deep water formation was found to be modulated by the Sun (Morley *et al*., 2011). The famous rains in Northern Ireland are affected by changes in solar activity (Swindles *et al*., 2012). Winds in Portugal blew particularly strong when the Sun was weak (Costas *et al*., 2012). Solar activity fluctuations and the North Atlantic Oscillation (NAO) have contributed to Italy's climate of the past 10,000 years (Scholz *et al*., 2012). A solar influence also could be detected in Italian salt marshes (Di Ritam 2013).

Noting "solar activity during the current sunspot minimum has fallen to levels unknown since the start of the 20th century" and "the Maunder minimum (about 1650–1700) was a prolonged episode of low solar activity which coincided with more severe winters in the United Kingdom and continental Europe," Lockwood *et al*. (2010) were "motivated by recent relatively cold winters in the UK" to investigate the possible connection between these severe winters and low solar activity. They identified "regionally anomalous cold winters by detrending the Central England temperature record using reconstructions of the northern hemisphere mean temperature" and discovered "cold winter excursions from the hemispheric trend" do indeed "occur more commonly in the UK during low solar activity, consistent with the solar influence on the occurrence of persistent blocking events in the eastern Atlantic." They state "colder UK winters (relative to the longer-term trend) can therefore be associated with lower open solar flux (and hence with lower solar irradiance and higher cosmic ray flux)."

Lockwood *et al.* are quick to note "this is a regional and seasonal effect relating to European winters and not a global effect." But they also note "average solar activity has declined rapidly since 1985 and cosmogenic isotopes suggest an 8% chance of a return to Maunder minimum conditions within the next 50 years (Lockwood, 2010)," suggesting "despite hemispheric warming, the UK and Europe could experience more cold winters than during recent decades."

Mangini *et al*. (2005) developed a highly resolved 2,000-year δ^{18}O proxy record of temperature obtained from a stalagmite recovered from Spannagel Cave in the Central Alps of Austria. They found the lowest temperatures of the past two millennia occurred during the Little Ice Age (AD 1400–1850), while the highest temperatures were found in the Medieval Warm Period (MWP: AD 800–1300). They report the highest temperatures of the MWP were "slightly higher than those of the top section of the stalagmite (1950 AD) and higher than the present-day temperature." At three different points during the MWP, their data indicate temperature spikes in excess of 1°C above present (1995–1998) temperatures.

Mangini *et al*. also report their temperature reconstruction compares well with reconstructions developed from Greenland ice cores (Muller and Gordon, 2000), Bermuda Rise ocean-bottom sediments (Keigwin, 1996), and glacier tongue advances and retreats in the Alps (Holzhauser, 1997; Wanner *et al*., 2000), as well as with the Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005). Considered together, they say, these several data sets "indicate that the MWP was a climatically distinct period in the Northern Hemisphere," emphasizing "this conclusion is in strong contradiction to the temperature reconstruction by the IPCC, which only sees the last 100 years as a period of increased temperature during the last 2000 years."

Mangini *et al*. also found "a high correlation between δ^{18}O and δ^{14}C, that reflects the amount of radiocarbon in the upper atmosphere," and they note this correlation "suggests that solar variability was a major driver of climate in Central Europe during the past 2 millennia." They report "the maxima of δ^{18}O coincide with solar minima (Dalton, Maunder, Sporer, Wolf, as well as with minima at around AD 700, 500 and 300)" and "the coldest period between 1688 and 1698 coincided with the Maunder Minimum." Also, in a linear-model analysis of the percent of variance of their full temperature reconstruction that is individually explained by solar and CO_2 forcing, they found the impact of the Sun was fully 279 times greater than that of the air's CO_2 concentration, noting "the flat evolution of CO_2 during the first 19 centuries yields almost vanishing correlation coefficients with the temperature reconstructions."

Two years later, Mangini *et al*. (2007) updated the 2005 study with additional data and compared it with the Hematite-Stained-Grain (HSG) history of ice-rafted debris in North Atlantic Ocean sediments developed by Bond *et al*. (2001). They found an undeniably good correspondence between the peaks and valleys of their δ^{18}O curve and the HSG curve. Recall from our previous discussion of Bond *et al*.'s work this conclusion: "Over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

Other researchers have found similar periodicities in their climate proxies. Turner *et al*. (2008), for example, found an ~1,500 year cycle in a climate history reconstructed from sediment cores extracted from two crater lake basins in central Turkey, which they indicate “may be linked with large-scale climate forcing” such as that found in the North Atlantic by Bond *et al*. (1997, 2001). In addition, McDermott *et al*. (2001) found evidence of millennial-scale climate cycles in a $\delta^{18}O$ record from a stalagmite in southwestern Ireland, as did Sbaffi *et al*. (2004) from two deep-sea sediment cores recovered from the Tyrrhenian Sea, which corresponded well with the North Atlantic solar-driven cycles of Bond *et al*. (1997).

In the Mediterranean Sea, Cini Castagnoli *et al*. (2002) searched for solar-induced variations in the $\delta^{13}C$ record of the foraminifera *Globigerinoides rubber* obtained from a sea core located in the Gallipoli terrace of the Gulf of Taranto (39°45’53”N, 17°53’33”E, depth of 178 m) over the past 1,400 years. Starting at the beginning of the 1,400-year record, the $\delta^{13}C$ values increased from about 0.4 per mil around 600 A.D. to a value of 0.8 per mil by 900 A.D. Thereafter, the $\delta^{13}C$ record remained relatively constant until about 1800, when it rose another 0.2 per mil to its present-day value of around 1.0 per mil.

Using statistical procedures, the authors identified three important cyclical components in their record, with periods of approximately 11.3, 100, and 200 years. Comparison of both the raw $\delta^{13}C$ and component data with the historical aurorae and sunspot time series, respectively, revealed the records are “associable in phase” and “disclose a statistically significant imprint of the solar activity in a climate record.” Three years later, Cini Castagnoli *et al*. (2005) extended the $\delta^{13}C$ temperature proxy from the Gulf of Taranto an additional 600 years, reporting an overall phase agreement between the climate reconstruction and variations in the sunspot number series that “favors the hypothesis that the [multi-decadal] oscillation revealed in $\delta^{13}C$ is connected to the solar activity.”

Chen *et al*. (2011) developed a high temporal resolution (four-year) sea surface temperature (SST) history based on a dinoflagelate cyst record obtained from a well-dated sediment core retrieved from a site in the Gulf of Taranto located at the distal end of the Po River discharge plume (39°50.07’N, 17°48.05’E). Their analysis revealed an era of “high stable temperatures between 60 BC and 90 AD followed by a decreasing trend between 90 AD and 200 AD.” And “consistent to earlier findings for the region,” they state “local air temperature during the Roman Period might have been warmer than that of the 20th century.” The authors write, “the observation of strong 11 years cyclicity in our records together with a strong visual correlation of our temperature and river discharge records with the global variation in $\Delta^{14}C$ anomalies suggest that solar activity might have been an important climate forcing factor during this time.”

Desprat *et al*. (2003) conducted a high-resolution pollen analysis of a sediment core retrieved from the central axis of the Ria de Vigo in the south of Galicia (42°14.07’N, 8°47.37’W) to study the climatic variability of the last three millennia in northwest Iberia. According to the authors, over the past 3,000 years there was “an alternation of three relatively cold periods with three relatively warm episodes.” In order of their occurrence, those periods were described by the authors as the “first cold phase of the Subatlantic period (975–250 BC),” “followed by the Roman Warm Period (250 BC–450 AD),” followed by “a successive cold period (450–950 AD), the Dark Ages,” which “was terminated by the onset of the Medieval Warm Period (950–1400 AD),” followed by “the Little Ice Age (1400–1850 AD), including the Maunder Minimum (at around 1700 AD),” which “was succeeded by the recent warming (1850 AD to the present).” Based on this “millennial-scale climatic cyclicity over the last 3000 years,” which parallels “global climatic changes recorded in North Atlantic marine records (Bond *et al*., 1997; Bianchi and McCave, 1999; Chapman and Shackelton, 2000),” Desprat *et al*. conclude “solar radiative budget and oceanic circulation seem to be the main mechanisms forcing this cyclicity in NW Iberia.”

Morellon *et al*. (2011) note, “in the context of present-day global warming, there is increased interest in documenting climate variability during the last millennium” because “it is crucial to reconstruct pre-industrial conditions to discriminate anthropogenic components (i.e., greenhouse gases, land-use changes) from natural forcings (i.e., solar variability, volcanic emissions).” They conducted a multi-proxy study of several short sediment cores recovered from Lake Estanya (42°02’N, 0°32’E) in the Pre-Pyrenean Ranges of northeast Spain, providing “a detailed record of the complex environmental, hydrological and anthropogenic interactions occurring in the area since medieval times.” They report “the integration of sedimentary facies, elemental and isotopic geochemistry, and biological proxies (diatoms, chironomids and pollen), together with a robust chronological control, provided by AMS radiocarbon dating and ^{210}Pb and ^{137}Cs radiometric techniques, enabled precise reconstruction of the main phases of environmental change, associated with the Medieval

Warm Period (MWP), the Little Ice Age (LIA) and the industrial era."

The 13 researchers identified the MWP as occurring in their record from AD 1150 to 1300, noting their pollen data reflect "warmer and drier conditions" in harmony with the higher temperatures of the Iberian Peninsula over the same time period documented by Martinez-Cortizas *et al*. (1999), the higher temperatures of the Western Mediterranean region found by Taricco *et al*. (2008), and the global reconstructions of Crowley and Lowery (2000) and Osborn and Briffa (2006), which "clearly document warmer conditions from the twelfth to fourteenth centuries." Morellon *et al*. conclude this warmth is "likely related to increased solar irradiance (Bard *et al*., 2000), persistent La Niña-like tropical Pacific conditions, a warm phase of the Atlantic Multidecadal Oscillation, and a more frequent positive phase of the North Atlantic Oscillation (Seager *et al*., 2007)."

Morellon *et al*. also note the occurrence of the LIA, which they recognize as occurring from AD 1300 to 1850. On the Iberian Peninsula, they report, "lower temperatures (Martinez-Cortizas *et al*., 1999) characterize this period," which "coincided with colder North Atlantic (Bond *et al*., 2001) and Mediterranean sea surface temperatures (Taricco *et al*., 2008) and a phase of mountain glacier advance (Wanner *et al*., 2008)." Following the LIA they identify the transition period of AD 1850–2004 that takes the region into the Current Warm Period.

In discussing these periods, the authors say "a comparison of the main hydrological transitions during the last 800 years in Lake Estanya and solar irradiance (Bard *et al*., 2000) reveals that lower lake levels dominated during periods of enhanced solar activity (MWP and post-1850 AD) and higher lake levels during periods of diminished solar activity (LIA)." Within the LIA they note periods of higher lake levels or evidence of increased water balance occurred during the solar minima of Wolf (AD 1282–1342), Sporer (AD 1460–1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1820).

Paleoclimatic studies from Europe provide more evidence for the global reality of solar-induced temperature oscillations pervading both glacial and interglacial periods, and these oscillations are looking more and more likely as the primary forcing agent responsible for driving temperature change during the Current Warm Period. The concurrent historical increase in the air's CO_2 content, on the other hand, has likely exerted only minimal influence.

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3.3.7 Other Geographical Regions

Van Geel *et al*. (1999) examined the relationship between variations in the abundances of the cosmogenic isotopes ^{14}C and ^{10}Be and millennial-scale climate oscillations during the Holocene and portions of the last great ice age. They write, "there is mounting evidence suggesting that the variation in solar activity is a cause for millennial-scale climate change," which is known to operate independently of the glacial-interglacial cycles forced by variations in Earth's orbit about the Sun. They add, "accepting the idea of solar forcing of Holocene and Glacial climatic shifts has major implications for our view of present and future climate," for it implies, as they note, "the climate system is far more sensitive to small variations in solar activity than generally believed" and "it could mean that the global temperature fluctuations during the last decades are partly, or completely explained by small changes in solar radiation."

Tyson *et al*. (2000) obtained a quasi-decadal-resolution record of oxygen and carbon-stable isotope data from a well-dated stalagmite recovered from Cold Air Cave in the Makapansgat Valley, 30 km southwest of Pietersburg, South Africa. They augmented that record with temperature data reconstructed from color variations in banded growth-layer laminations of the stalagmite derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981–1995, which had a correlation of +0.78 that was significant at the 99 percent confidence level.

The authors found both the Little Ice Age (prevailing from about AD 1300 to 1800) and the Medieval Warm Period (prevailing from before AD 1000 to around 1300) to be distinctive features of the climate of the last millennium. Compared with the period 1961–1990, the Little Ice Age, "a widespread event in South Africa specifically and southern Africa generally," was characterized by a mean annual temperature depression of about 1°C at its coolest point. The Medieval Warm Period, by contrast, was as much as 3–4°C warmer at its warmest point. The researchers also note the coolest point of the Little Ice Age corresponded with the Maunder Minimum of sunspot activity and the Medieval Warm Period corresponded with the Medieval Maximum in solar activity.

In a study demonstrating a solar-climate link on shorter decadal to centennial time scales, Domack *et al*. (2001) examined ocean sediment cores obtained from the Palmer Deep on the inner continental shelf of the western Antarctic Peninsula (64° 51.71' S, 64° 12.47' W) to produce a high-resolution proxy temperature history of that area spanning the past 13,000 years. They identified five prominent palaeo-environmental intervals over the past 14,000 years: (1) a "Neoglacial" cool period beginning 3,360 years ago and continuing to the present, (2) a mid-Holocene climatic optimum from 9,070 to 3,360 years ago, (3) a cool period beginning 11,460 years ago and ending at 9,070 years ago, (4) a warm period from 13,180 to 11,460 years ago, and (5) cold glacial conditions prior to 13,180 years ago. Spectral analyses of the data revealed decadal and centennial-scale temperature cycles superimposed upon these broad climatic intervals. Throughout the current Neoglacial period, they report finding "very significant" (above the 99 percent confidence level) peaks, or oscillations, that occurred at intervals of 400, 190, 122, 85, and 70 years, which they suggest are perhaps driven by solar variability.

Dima *et al*. (2005) performed Singular Spectrum Analysis on a Rarotonga coral-based sea surface temperature (SST) reconstruction from the warmer ocean waters off the Cook Islands, South Pacific Ocean in an effort to determine the dominant periods of multidecadal variability in the series over the period 1727–1996. Their work revealed two dominant multidecadal cycles with periods of about 25 and 80 years. These modes of variability were determined to be similar to multidecadal modes found in the global SST field of Kaplan *et al*. (1998) for the period 1856–1996. The ~25-year cycle was found to be associated with the well-known Pacific Decadal Oscillation, whereas the ~80-year cycle was determined to be "almost identical" to a pattern of solar forcing found by Lohmann *et al*. (2004), which, according to Dima *et al*., "points to a possible solar origin" of this mode of SST variability.

Bard and Frank (2006) reviewed what is known and unknown about solar variability and its effects on Earth's climate over the past few decades, the past few centuries, the entire Holocene, and orbital timescales. With respect to the three suborbital time scales, Bard and Frank conclude, "it appears that solar fluctuations were involved in causing widespread but limited climatic changes, such as the Little Ice Age (AD 1500–1800) that followed the Medieval Warm Period (AD 900–1400)." They write, "the weight of evidence suggests that solar changes have contributed to small climate oscillations occurring on time scales of a few centuries, similar in type to the fluctuations classically described for the last millennium: The so-called Medieval Warm Period (AD 900–1400) followed on by the Little Ice Age (AD 1500–1800)."

Bard and Frank note, "Bond *et al*. (1997, 2001) followed by Hu *et al*. (2003) proposed that variations of solar activity are responsible for quasi-periodic climatic and oceanographic fluctuations that follow cycles of about one to two millennia." They write, "the succession from the Medieval Warm Period to the Little Ice Age would thus represent the last [such] cycle," leading them to conclude "our present climate is in an ascending phase on its way to attaining a new warm optimum" resulting from some form of solar variability. In addition, they note, "a recent modeling study suggests that an apparent 1500-year cycle could arise from the superimposed influence of the 90 and 210 year solar cycles on the climate system, which is characterized by both nonlinear dynamics and long time scale memory effects (Braun *et al*. 2005)."

The studies discussed in this and previous subsections examining solar influence on temperature demonstrate the warming of Earth since the termination of the Little Ice Age is not unusual or different from other climate changes of the past millennium, when atmospheric CO_2 concentrations were stable, lower than at present, and not responsible for the observed variations in temperature. This further suggests the warming of the past century had little to do with the contemporaneous historical increase in the air's CO_2 content.

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3.4 Precipitation

Many researchers have examined historical proxy temperature changes over the past millennia and beyond in an attempt to quantify the magnitude, frequency, and causes of natural climate variability. However, temperature is not always the best measure of climate, and it is certainly not the only measure. Some studies, for example, have examined the millennial range and rate of change of hydrologic and atmospheric circulation; changes in these parameters are important because they are involved in more than half of Earth's poleward transfer of heat (Peixoto and Oort, 1992).

In one such study, Maasch *et al*. (2005) examined changes in eight well-dated high-resolution climate-related records over the past two millennia: K^+ concentrations from the GISP2 ice core in Greenland, Na^+ concentrations from the Siple Dome ice core in Antarctica, percent Ti from an ocean sediment core in the Cariaco basin, Fe intensity from a marine core near the coast of mid-latitude Chile, oxygen isotope fractions from Punta Laguna near the Yucatan, carbon isotope data from a speleothem in Makapansgat, South Africa, percent of shallow water diatoms from Lake Victoria, and lake levels from Lake Naivasha in equatorial Africa. The eight data sets were compared with a history of atmospheric $\Delta^{14}C$, a proxy for solar variability obtained from tree rings, to ascertain what, if any, solar influence operated on these parameters.

Comparison of the $\Delta^{14}C$ solar proxy data with the eight climate-related data sets revealed over the past 2,000 years there has been a "strong association between solar variability and globally distributed climate change." This "remarkable coherence" among the data sets was particularly noticeable in the Medieval Warm Period to Little Ice Age transition, as well as throughout the Little Ice Age.

In this section we review studies that show past trends in precipitation are likely explained better by solar variability than by the IPCC's preferred explanation, rising atmospheric CO_2 concentrations.

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3.4.1 North America

Kristjansson *et al*. (2002) examined the relationship between the Sun and low-level clouds, which are correlated with precipitation. They note solar irradiance "varies by about 0.1% over the 11-year solar cycle, which would appear to be too small to have an impact on climate." Nevertheless, they report "persistent claims have been made of 11-year signals in various meteorological time series, e.g., sea surface temperature (White *et al*., 1997) and cloudiness over North America (Udelhofen and Cess, 2001)."

Kristjansson *et al*. "re-evaluate[d] the statistical relationship between low cloud cover and solar activity adding 6 years of ISCCP [International Satellite Cloud Climatology Project] data that were recently released." For the period 1983–1999, they compared temporal trends of solar irradiance at the top of the atmosphere with low cloud cover trends derived from satellite-borne instruments that provided two measures of cloud cover: full temporal coverage and daytime-only coverage. They found "solar irradiance correlates well with low cloud cover," with the significance level of the correlation being 98 percent for full temporal coverage and 90 percent for daytime-only coverage. In addition, as would be expected if the variations in cloud cover were driven by variations in solar irradiance, they also report lagged correlations between the two parameters revealed a maximum correlation between solar irradiance and low cloud cover when the former leads the latter by one month for full temporal coverage and by four months for daytime-only coverage.

Kristjansson *et al*. observed "low clouds appear to be significantly inversely correlated with solar irradiance," leading them to suggest a possible physical mechanism that could explain this phenomenon. This mechanism "acts through UV [ultraviolet radiation] in the stratosphere affecting tropospheric planetary waves and therefore the subtropical highs, modulated by an interaction between sea surface temperature [SST] and lower tropospheric static stability," which "relies on a positive feedback between changes in SST and low cloud cover changes of opposite sign, in the subtropics." Based on experimentally determined values of factors that enter into this scenario, they obtained a value for the amplitude of the variation in low cloud cover over a solar cycle that "is very close to the observed amplitude."

Other authors have examined lake level fluctuations, which are generally highly dependent on precipitation levels. Cumming *et al*. (2002), for example, studied a sediment core retrieved from Big Lake (51°40'N, 121°27'W) on the Cariboo Plateau of British Columbia, Canada, carefully dating it and deriving estimates of changes in precipitation-sensitive limnological variables (salinity and lake depth) from transfer functions based on modern distributions of diatom assemblages in 219 lakes from western Canada.

On the basis of observed changes in patterns of the floristic composition of diatoms over the past 5,500 years, Cumming *et al*. report "alternating millennial-scale periods of high and low moisture availability were inferred, with abrupt transitions in diatom communities occurring 4960, 3770, 2300 and 1140 cal. yrs. BP." They also find "periods of inferred lower lake depth correspond closely to the timing of worldwide Holocene glacier expansions" and the mean length of "the relatively stable intervals between the abrupt transitions ... is similar to the mean Holocene pacing of IRD [ice rafted debris] events ... in the North Atlantic," described by Bond *et al*. (1997) and attributed to "solar variability amplified through oceanic and atmospheric dynamics," as detailed by Bond *et al*. (2001).

Li *et al*. (2006, 2007) also developed a precipitation proxy from a lake-level record, based on lithologic and mineral magnetic data from the Holocene sediments of White Lake, New Jersey, northeastern USA (41°N, 74.8°W), the characteristics of which they compared with a host of other paleoclimatic reconstructions from this region and beyond.

According to the authors of these two papers (Li *et al*., 2006; 2007), the lake-level history revealed low lake levels at ~1.3, 3.0, 4.4, and 6.1 thousand years before present. Comparison of the results with drift-ice records from the North Atlantic Ocean according to Li *et al*. (2007) "indicates a striking correspondence," as they "correlate well with cold events 1, 2, 3 and 4 of Bond *et al*. (2001)." They also report a comparison of their results with those of other land-based studies suggests "a temporally coherent pattern of climate variations at a quasi-1500-year periodicity at least in the Mid-Atlantic region, if not the entire northeastern USA." In addition, they note "the Mid-Atlantic region was dominated by wet conditions, while most parts of the conterminous USA experienced droughts, when the North Atlantic Ocean was warm."

The three researchers say the dry-cold correlation they found "resembles the modern observed relationship between moisture conditions in eastern North America and the North Atlantic Oscillation (NAO), but operates at millennial timescales, possibly through modulation of atmospheric dynamics by solar forcing," In this regard they write the Sun-climate link on millennial timescales has "been demonstrated in several records (e.g., Bond *et al*., 2001; Hu *et al*., 2003; Niggemann *et al*., 2003), supporting solar forcing as a plausible mechanism for modulating the AO [Arctic Oscillation]/NAO at millennial timescales."

Dean *et al*. (2002) analyzed the varve thickness and continuous gray-scale density of sediment cores taken from Elk Lake, Minnesota (47°12'N, 95°15'W) for the past 1,500 years. They identified significant periodicities throughout the record, including multidecadal periodicities of approximately 10, 29, 32, 42, and 96 years, and a strong multicentennial periodicity of about 400 years, leading them to wonder whether the observed periodicities are manifestations of solar-induced climate signals, for which they present strong correlative evidence. The 10-year oscillation was found to be strongest in the time series between the fourteenth and nineteenth centuries, during the Little Ice Age, and may have been driven by the 11-year sunspot cycle.

Lozano-Garcia *et al*. (2007) conducted a high-resolution multi-proxy analysis of pollen, charcoal particles, and diatoms found in the sediments of Lago Verde (18°36'46" N, 95°20'52"W)—a small closed-basin lake on the outskirts of the Sierra de Los Tuxtlas (a volcanic field on the coast of the Gulf of Mexico)—which covered the past 2,000 years. The five Mexican researchers say their data "provide evidence that the densest tropical forest cover and the deepest lake of the last two millennia were coeval with the Little Ice Age, with two deep lake phases that follow the Sporer and Maunder minima in solar activity." In addition, they suggest "the high tropical pollen accumulation rates limit the Little Ice Age's winter cooling to a maximum of 2°C," and they conclude the "tropical vegetation expansion during the Little Ice Age is best explained by a reduction in the extent of the dry season as a consequence of increased meridional flow leading to higher winter precipitation." Lozano-Garcia *et al*. conclude, "the data from Lago Verde strongly suggest that during the Little Ice Age lake levels and vegetation at Los Tuxtlas were responding to solar forcing and provide further evidence that solar activity is an important element controlling decadal to centennial scale climatic variability in the tropics (Polissar *et al*., 2006) and in general over the North Atlantic region (Bond *et al*., 2001; Dahl-Jensen *et al*., 1998)."

Hughes *et al*. (2006) derived a multi-proxy palaeoclimate record from Nordan's Pond Bog, a coastal plateau bog in Newfoundland, based on "analyses of plant macrofossils, testate amoebae and the degree of peat humification," enabling them to create "a single composite reconstruction of bog surface wetness (BSW)" they compare with "records of cosmogenic isotope flux."

"At least 14 distinctive phases of increased BSW may be inferred from the Nordan's Pond Bog record," they write, commencing at 8,270 cal. years BP, and "comparisons of the BSW reconstruction with records of cosmogenic isotope flux ... suggest a persistent link between reduced solar irradiance and increased BSW during the Holocene." Hughes *et al*. further conclude the "strong correlation between increased ^{14}C production [which accompanies reduced solar activity] and phases of maximum BSW supports the role of solar forcing as a persistent driver of changes to the atmospheric moisture balance throughout the Holocene." Consequently, the authors state, "evidence suggesting a link between solar irradiance and sub-Milankovitch-scale palaeoclimatic change has mounted" and the "solar hypothesis, as an explanation for Holocene climate change, is now gaining wider acceptance."

Asmerom *et al*. (2007) developed a high-resolution Holocene climate proxy for the southwest United States from δ^{18}O variations in a stalagmite obtained in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw δ^{18}O data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." Their cross-spectral analysis of the Δ^{14}C and δ^{18}O data confirmed the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. They suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

Schmidt *et al*. (2012) found Florida was drier when the Sun was weak and wetter when the Sun was strong. And Nichols *et al*. (2012) note the rains in Maine over the past 7,000 years have been controlled by the sun.

Since the warming of the twentieth century appears to represent the most recent rising phase of the Bond cycle, which in its previous rising phase produced the Medieval Warm Period (see Bond *et al*., 2001), and since we could still be embedded in that rising temperature phase, it is reasonable to expect the desert southwest of the United States could experience more intense aridity while wetter conditions prevail in the monsoon regions of Asia, without greenhouse gases playing any role.

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3.4.2 South America

Nordemann *et al*. (2005) analyzed tree rings from species sensitive to fluctuations in precipitation from the southern region of Brazil and Chile along with sunspot data via harmonic spectral and wavelet analysis in an effort to obtain a greater understanding of the effects of solar activity, climate, and geophysical phenomena on the continent of South America. The tree-ring samples from Brazil covered 200 years and those from Chile covered 2,500 years. The spectral analysis revealed periodicities in the tree rings that corresponded well with the de Vries-Suess (~200 yr), Gleissberg (~80 yr), Hale (~22 yr), and Schwabe (~11 yr) solar activity cycles; wavelet cross-spectrum analysis of sunspot number and tree-ring growth revealed a clear relation between the tree-ring and solar series.

Baker *et al*. (2005) used a sediment core retrieved from the main basin of Lake Titicaca (16°S, 69°W) on the Altiplano of Bolivia and Peru to reconstruct the lake-level history of that South American water body over the past 13,000 years at decadal to multidecadal resolution based on $\delta^{13}C$ measurements of sediment bulk organic matter. The authors report "the pattern and timing of lake-level change in Lake Titicaca is similar to the ice-rafted debris record of Holocene Bond events, demonstrating a possible coupling between precipitation variation on the Altiplano and North Atlantic sea-surface temperatures." Noting "cold periods of the Holocene Bond events correspond with periods of increased precipitation on the Altiplano," they further conclude "Holocene precipitation variability on the Altiplano is anti-phased with respect to precipitation in the Northern Hemisphere monsoon region." They add, "the relationship between lake-level variation at Lake Titicaca and Holocene Bond events also is supported by the more coarsely resolved (but very well documented) record of water-level fluctuations over the past 4000 years based on the sedimentology of cores from the shallow basin of the lake (Abbott *et al*., 1997)."

Haug *et al*. (2001) utilized the titanium and iron concentrations of an ocean sediment core taken from a depth of 893 meters in the Cariaco Basin on the Northern Shelf of Venezuela (10°42.73'N, 65°10.18'W) to infer variations in the hydrologic cycle over northern South America over the past 14,000 years. They found titanium and iron concentrations were lower during the Younger Dryas cold period between 12.6 and 11.5 thousand years ago, corresponding to a weakened hydrologic cycle with less precipitation and runoff. During the Holocene Optimum (10.5 to 5.4 thousand years ago), concentrations of these metals remained at or near their highest values, suggesting wet conditions and an enhanced hydrologic cycle for more than five thousand years. The largest century-scale variations in precipitation are inferred in the record between approximately 3.8 and 2.8 thousand years ago, as the amounts of these metals in the sediment record varied widely over short time intervals. Higher precipitation was noted during the Medieval Warm Period from 1.05 to 0.7 thousand years ago, followed by drier conditions associated with the Little Ice Age (between 550 and 200 years ago).

The authors say the regional changes in precipitation "are best explained by shifts in the mean latitude of the Atlantic Intertropical Convergence Zone," which, in turn, "can be explained by the Holocene history of insolation, both directly and through its effect on tropical Pacific sea surface conditions."

In South America the Sun has controlled the distribution and intensity of the monsoon rains (Vuille *et al*., 2012), a solar influence on precipitation also has been found for Brazil (Gusec and Martin, 2012; Rampelotto *et al*., 2012), and solar cycles have been detected in the water masses of the deep sea (Seidenglanz *et al*., 2012). The field of research in solar-climate interaction is more active than ever (de Wit *et al*., 2010; Stauning, 2011; Raspopov *et al*., 2011; Kern *et al*., 2012).

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3.4.3 Africa

Neff *et al*. (2001) investigated the relationship between a ^{14}C tree-ring record and a delta^{18}O proxy record of monsoon rainfall intensity as recorded in calcite delta^{18}O data obtained from a stalagmite in northern Oman. The correlation between the two data sets, covering the period 9,600–6,100 years before present, was reported to be "extremely strong." A spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the delta^{18}O record and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Because variations in ^{14}C tree-ring records are generally attributed to variations in solar activity and intensity, and because of this particular ^{14}C record's strong correlation with the delta^{18}O record and the closely corresponding results of the spectral analyses, Neff *et al*. conclude there is "solid evidence" that both signals (the ^{14}C and delta^{18}O records) are responding to solar forcing.

Stager *et al*. (2003) studied changes in diatom assemblages preserved in a sediment core extracted from Pilkington Bay, Lake Victoria, together with diatom and pollen data acquired from two nearby sites. According to the authors, the three coherent data sets revealed a "roughly 1400- to 1500-year spacing of century-scale P:E [precipitation: evaporation] fluctuations at Lake Victoria," which "may be related to a ca. 1470-year periodicity in northern marine and ice core records that has been linked to solar variability (Bond *et al*., 1997; Mayewski *et al*., 1997)."

Further support of Stager *et al*.'s thesis comes from Verschuren *et al*. (2000), who developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on lake-level and salinity fluctuations of a small crater-lake basin in Kenya, as reconstructed from sediment stratigraphy and the species compositions of fossil diatom and midge assemblages. They compared this history with an equally long record of atmospheric $^{14}CO_2$ production, which is a proxy for solar radiation variations.

They found equatorial east Africa was significantly drier than today during the Medieval Warm Period from AD 1000 to 1270 and relatively wet during the Little Ice Age from AD 1270 to 1850. This latter period was interrupted by three periods of prolonged dryness: 1390–1420, 1560–1625, and 1760–1840. These "episodes of persistent aridity," in the words of the authors, were "more severe than any recorded drought of the twentieth century." They note their results "corroborate findings from north-temperate dryland regions that instrumental climate records are inadequate to appreciate the full range of natural variation in drought intensity at timescales relevant to socio-economic activity." Today, almost every new storm of significant size, every new flood, or every new hint of drought almost anywhere in the world brings claims the weather is becoming more extreme than ever before as a consequence of global warming. Verschuren *et al.* remind us there were more intense droughts in the centuries preceding the recent rise in the atmosphere's CO_2 content.

Verschuren *et al.* discovered "all three severe drought events of the past 700 years were broadly coeval with phases of high solar radiation, and the intervening periods of increased moisture were coeval with phases of low solar radiation." They state variations in solar radiative output "may have contributed to decade-scale rainfall variability in equatorial east Africa." This conclusion is characterized as robust by Oldfield (2000), who suggests their results "provide strong evidence for a link between solar and climate variability."

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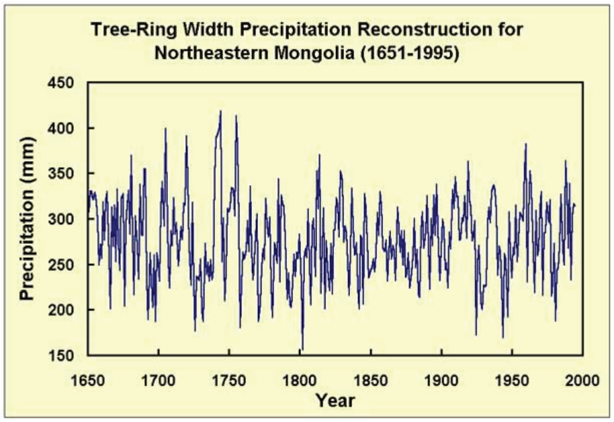
3.4.4 Asia & Australia

Pederson *et al*. (2001) utilized tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for this region over the period 1651–1995.

Analyses of both standard deviations and five-year intervals of extreme wet and dry periods revealed "variations over the recent period of instrumental data are not unusual relative to the prior record" (see Figure 3.4.4.1). The authors state, however, the reconstructions "appear to show more frequent extended wet periods in more recent decades," but they note this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." More important to the present discussion, however, is their observation that spectral analysis of the data revealed significant periodicities of around 12 and 20-24 years, suggesting "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Tan *et al*. (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau's northeast margin since AD 960 based on an analysis of Chinese historical records, which they compared with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories. They found "high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere." They also found "good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record." These findings harmonize, in their words, with "numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene," citing 22 scientific references. The researchers conclude the "synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity."

Paulsen *et al*. (2003) utilized "high-resolution records of $\delta^{13}C$ and $\delta^{18}O$ in stalagmite SF-1 from Buddha Cave [33°40'N, 109°05'E] ... to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." They identified several major climatic episodes, including the Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and twentieth century warming, "lending support to the global extent of these events." With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet, followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Current Warm Period. Some of the Current Warm Period's variability is undoubtedly due to the much finer one-year time resolution of the past 150 years of the record as compared to the three- to four-year resolution of the prior 1,120 years. The major droughts centered on AD 1835, 1878, and 1955 were very well delineated by this improved resolution.



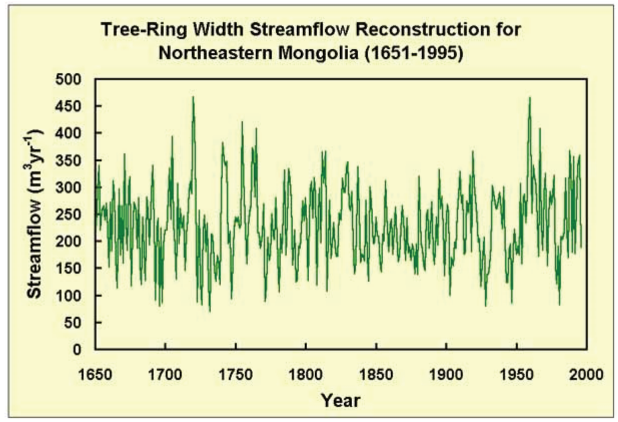


Figure 3.4.4.1. Reconstructed precipitation and streamflow records for northeastern Mongolia over the period 1651-1995. Adapted from Pederson, N., Jacoby, G.C., D'Arrigo, R.D., Cook, E.R., and Buckley, B.M. 2001. Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651-1995. *Journal of Climate* **14**: 872–881.

The data also revealed a number of other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture. Paulsen *et al*. attributed most of these higher-frequency cycles to cyclical solar and lunar phenomena, concluding the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

Liu *et al*. (2012) point out "climate change is consistently associated with changes in a number of components of the hydrological cycle," including "precipitation patterns and intensity, and extreme weather events." To "provide advice for water resource management under climate change," they conducted a study of the subject in the Guangdong Province of Southern China, which occupies a land area of approximately 178,000 km^2 and has a population of just over 96 million people (as of 2009).

Liu *et al*. analyzed "trends of annual, seasonal and monthly precipitation in southern China (Guangdong Province) for the period 1956–2000 ... based on the data from 186 high-quality gauging stations" and employed "statistical tests, including the Mann-Kendall rank test and wavelet analysis" to determine whether the precipitation series exhibited any regular trends or periodicities.

The four researchers report "annual precipitation has a slightly decreasing trend in central Guangdong and slight increasing trends in the eastern and western areas of the province," but "all the annual trends are not statistically significant at the 95% confidence level." In addition, they discovered "average precipitation increases in the dry season in central Guangdong, but decreases in the wet season," such that "precipitation becomes more evenly distributed within the year." They note, "the results of wavelet analysis show prominent precipitation with periods ranging from 10 to 12 years in every sub-region in Guangdong Province." Comparing precipitation with the 11-year sunspot cycle, they find "the annual precipitation in every sub-region in Guangdong province correlates with sunspot Number with a 3-year lag." Liu *et al*.'s analysis suggests precipitation in China's Guangdong Province has become both less extreme and less variable during the 1956–2000 global warming.

Two recent papers by Zhao *et al.* (2012) and Wang and Zhao (2012), scientists at the National Satellite Meteorological Center of China Meteorological Administration, offered practical insights using instrumental records to consider the relationship between solar activity and precipitation. They studied all precipitation records across the whole of China covering all monthly data series but found robust correlations only for the month of June and for specific regions. Wang and Zhao (2012) report:

> Six different statistical methods (i.e., correlation, difference, prominent period, variance contribution, scale-averaged spectrum, and cross spectrum) are used to test for regional differences in the relationship between the 11 year sunspot cycle and June precipitation in China during the 20th century. In the Huaihe River basin (HRB) of central China, located at the marginal region of

> the East Asian summer monsoon (EASM), there exists a reliable positive-correlation relationship between the 11 year sunspot cycle and June precipitation; whereas, possible negative and very weak positive correlations in the south of the middle–lower Yangtze River Region and the HeTao Basin (HTB), located in the interior of the EASM and the westerlies, respectively. The reasons for these regional differences are investigated, revealing that the marginal region of EASM may be more sensitive to solar forcing than is its interior, which results in the HRB becoming the most susceptible (strongest correlation) region. That is to say, in June during the high sunspot number (SSN) years, the influence of the EASM is significantly greater and more to the north than that in June during the low SSN years, causing the HRB to be mainly influenced by the EASM (westerlies) in June during the high (low) SSN years. The northward expansion of the June EASM probably resulted from enhancement of the low-level southwesterly monsoon flow over the northern tropical Indian Ocean, combined with an expansion of the western Pacific subtropical high at times of high SSN.

Further research confirms the solar-climate link with respect to precipitation. In China's Taklimakan Desert, oases blossomed in sync with solar millennial scale cycles (Zhao *et al*., 2012), and temperatures on the Tibetan plateau followed the sun's moods (Liu *et al*., 2011). Yu *et al*. (2012) found the East Asian monsoon to be controlled by solar activity changes, while Wu *et al*. (2012) found water currents of the East China Sea varied according to the sun's behavior. The climate of the Baikal Lake was shown by Murakami *et al*. (2012) to be correlated with solar activity, and the rains in Southeast Australia were in sync with the solar pattern (Kemp *et al*., 2012). Natural climate cycles appear to have led to the collapse of the powerful Indus Civilization (Giosan *et al*., 2012).

The Indian monsoons have strengthened and weakened according to the rhythm of the sun over the past 150 years (van Loon and Meehl, 2012). Rains on the Tibetan Plateau stopped whenever the sun weakened (Sun and Liu, 2012). Corals in Japan died during cold phases triggered by low solar activity (Hamanaka *et al*., 2012). A marked solar influence on Japanese climate was found in studies by Yamaguchi *et al*. (2010) and Muraki *et al*. (2011). Wet phases in Lake Aral were associated with solar high activity phases (Huang *et al*., 2011).

Precipitation in Asia clearly is determined by cycles, many of which are solar-driven and nearly all of which are independent of the air's CO_2 concentration.

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3.4.5 Europe

Mauquoy *et al*. (2004) reviewed the principles of ^{14}C wiggle-match dating, its limitations, and the insights it has provided about the timing and possible causes of climate change during the Holocene. They report "analyses of microfossils and macrofossils from raised peat bogs by Kilian *et al*. (1995), van Geel *et al*. (1996), Speranza *et al*. (2000), Speranza (2000) and Mauquoy *et al*. (2002a, 2002b) have shown that climatic deteriorations [to cooler and wetter conditions] occurred during periods of transition from low to high delta ^{14}C (the relative deviation of the measured ^{14}C activity from the standard after correction for isotope fractionation and radioactive decay; Stuiver and Polach, 1977)." This close correspondence suggests "changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BC (discussed in detail by van Geel *et al*., 1996, 1998, 1999, 2000) and the 'Little Ice Age' series of palaeoclimatic changes."

With respect to how the Sun may have driven the changes, the European scientists suggest two possibilities: "increased cosmic ray intensity, stimulating cloud formation and precipitation (Svensmark and FriisChristensen, 1997)," and "reduced solar UV intensity, causing a decline of stratospheric ozone production and cooling as a result of less absorption of sunlight (Haigh, 1996, 2001)." Noting "modeling results of Shindell *et al*. (2001) suggest solar-induced variations of ozone production could drive temperature changes in the middle and lower atmospheres, which in turn could cause changes in the North Atlantic Oscillation and the Arctic Oscillation," they tentatively conclude the solar UV mechanism may be the more likely of the two possibilities.

Blaauw *et al*. (2004) point out "Raised bogs are dependent on precipitation alone for water and nutrients," and each of the species of plants found in them have specific requirements with respect to depth of water table. As a result, the vertical distribution of macro- and micro-fossils in raised bogs reveals much about past changes in local moisture conditions, especially, the authors note, "about changes in effective precipitation (precipitation minus evapo-transpiration)." At the same time, changes in the carbon-14 content of bog deposits reveal something about solar activity, because, as Blaauw *et al*. describe the connection, "a decreased solar activity leads to less solar wind, reduced shielding against cosmic rays, and thus to increased production of cosmogenic isotopes [such as ^{14}C]." Consequently, it is possible to compare the histories of the two records (effective precipitation and $\delta^{14}C$) and see if inferred changes in climate bear any relationship to inferred changes in solar activity.

Two cores of mid-Holocene raised-bog deposits in the Netherlands were ^{14}C "wiggle-match" dated by the authors at high precision, using the technique described by Kilian *et al*. (1995, 2000) and Blaauw *et al*. (2003), and changes in local moisture conditions were inferred from the changing species composition of consecutive series of macrofossil samples. They found nine of 11 major mid-Holocene $\delta^{14}C$ increases, "probably caused by declines in solar activity," were coeval with major wet-shifts "probably caused by climate getting cooler and/or wetter." In the case of the significant wet-shift at the major $\delta^{14}C$ rise in the vicinity of 850 BC, they note this prominent climatic cooling has been independently documented in many parts of the world, including "the North Atlantic Ocean (Bond *et al*., 2001), the Norwegian Sea (Calvo *et al*., 2002) [see also Andersson *et al*. (2003)], Northern Norway (Vorren, 2001), England (Waller *et al*., 1999), the Czech Republic (Speranza *et al*., 2000, 2002), central southern Europe (Magny, 2004), Chile (van Geel *et al*., 2000), New Mexico (Armour *et al*., 2002) and across the continent of North America (Viau *et al*., 2002)."

Blaauw *et al*. (2003) say their findings "add to the accumulating evidence that solar variability has played an important role in forcing climatic change during the Holocene."

Cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen) by Björck and Clemmensen (2004) were examined for their content of wind-transported clastic material via a systematic count of quartz grains of diameter 0.2–0.35 mm and larger than 0.35 mm to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter storminess in that part of the world. According to the authors, "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." They note "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," while "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

Björck and Clemmensen also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They specifically note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)," while high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475" coincide with the Sporer Minimum of AD 1420–1530. The latter three peaks in winter storminess, they note, all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Several researchers have studied the precipitation histories of regions along the Danube River in western Europe and their effects on river discharge, with some suggesting an anthropogenic signal is present in the latter decades of the twentieth century and is responsible for that period's drier conditions. Ducic (2005) examined such claims by analyzing observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He notes the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was practically equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. In addition, the discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be "completely inside the limits of the whole series" and only slightly (38 m^3s^{-1} or 0.7 percent) less than the 260-year mean of 5356 m^3s^{-1}. Ducic concludes "modern discharge fluctuations do not point to [a] dominant anthropogenic influence." His correlative analysis suggests the detected cyclicity in the record could "point to the domination of the influence of solar activity."

Holzhauser *et al*. (2005) present high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, the northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year temperature and precipitation climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest of all glaciers located in the European Alps.

Near the beginning of the period studied, the three researchers report "during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today," noting "the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al*., 2003)." After an intervening unnamed cold-wet phase, when the glacier grew in both mass and length, they state, "during the Iron/Roman Age Optimum between c. 200 BC and AD 50," perhaps better known as the Roman Warm Period, the glacier again retreated and "reached today's extent or was even somewhat shorter than today." Next came the Dark Ages Cold Period followed by "the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300." They note the latter cold-wet phase was "characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60," following which the glacier began its latest and still-ongoing recession in 1865.

Data pertaining to the Gorner glacier (the second largest of the Swiss Alps) and the Lower Grindelwald glacier of the Bernese Alps tell much the same story, Holzhauser *et al*. report these glaciers and the Great Aletsch glacier "experienced nearly synchronous advances" throughout the study period. The Swiss and French scientists report "glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity," which in their estimation "suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlén, 1973; Magny, 1993; van Geel *et al*., 1996; Bond *et al*., 2001)." They conclude by stating "a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene."

Lamy *et al*. (2006) used paleoenvironmental proxy data for ocean properties, eolian sediment input, and continental rainfall based on high-resolution analyses of sediment cores from the southwestern Black Sea and the northernmost Gulf of Aqaba to infer hydroclimatic changes in northern Anatolia and the northern Red Sea region during the last ~7500 years. That reconstructed hydroclimatic history was compared with $\Delta^{14}C$ periodicities evident in the tree-ring data of Stuiver *et al*. (1998). The researchers found "pronounced and coherent" multicentennial variations they conclude "strongly resemble modern temperature and rainfall anomalies related to the Arctic Oscillation/North Atlantic Oscillation (AO/NAO)." In addition, they state "the multicentennial variability appears to be similar to changes observed in proxy records for solar output changes," although "the exact physical mechanism that transfers small solar irradiance changes either to symmetric responses in the North Atlantic circulation or to atmospheric circulation changes involving an AO/NAO-like pattern, remains unclear."

In 2012 Dermody *et al*. found solar-driven millennial scale cycles controlled wet and drought phases in the Mediterranean region during Roman times.

Each of these studies indicates cyclical solar activity induces cyclical precipitation activity in Europe. As Lamy *et al*. (2006) note, "the impact of (natural) centennial-scale climate variability on future climate projections could be more substantial than previously thought."

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3.5 Other Climatic Variables

In the previous two sections of this chapter we examined empirical observations of a solar influence on temperature and precipitation. In this section we examine empirical observations of the Sun's influence on other climate variables, including droughts, floods, monsoons, and streamflow.

3.5.1 Droughts

The IPCC claims Earth's climate is becoming more variable and extreme as a result of CO_2-induced global warming, and it forecasts increasing length and severity of drought as one of the consequences. In Chapter 7 of this report, addressing extreme weather, we will present evidence that modern drought frequency and severity fall well within the range of natural variability. Here, we consider the issue of attribution, specifically investigating the natural influence of the Sun on drought. We begin with a review of the literature on droughts in the United States.

According to Cook *et al*. (2007), recent advances in the reconstruction of past drought periods over North America "have revealed the occurrence of a number of unprecedented megadroughts over the past millennium that clearly exceed any found in the instrumental records." They state "these past megadroughts dwarf the famous droughts of the twentieth century, such as the Dust Bowl drought of the 1930s, the southern Great Plains drought of the 1950s, and the current one in the West that began in 1999." These dramatic droughts pale when compared to "an epoch of significantly elevated aridity that persisted for almost 400 years over the AD 900–1300 period," they write.

Of central importance to North American drought formation "is the development of cool 'La Niña-like' SSTs in the eastern tropical Pacific," the note. Paradoxically, as they describe the situation, "warmer conditions over the tropical Pacific region lead to the development of cool La Niña-like SSTs there, which is drought inducing over North America." In further explaining the mechanics of this phenomenon, on which both "model and data agree," Cook *et al*. state, "if there is a heating over the entire tropics then the Pacific will warm more in the west than in the east because the strong upwelling and surface divergence in the east moves some of the heat poleward"; as a result, "the east-west temperature gradient will strengthen, so the winds will also strengthen, so the temperature gradient will increase further, ... leading to a more La Niña-like state." They add "La Niña-like conditions were apparently the norm during much of the Medieval period when the West was in a protracted period of elevated aridity and solar irradiance was unusually high."

Yu and Ito (1999) studied a sediment core from a closed-basin lake in the northern Great Plains of North America, producing a 2,100-year record that revealed four dominant periodicities of drought matching "in surprising detail" similar periodicities of various solar indices. The correspondence was so close, they state "this spectral similarity forces us to consider solar variability as the major cause of century-scale drought frequency in the northern Great Plains."

Dean and Schwalb (2000) derived a similar-length record of drought from sediment cores extracted from Pickerel Lake, South Dakota, which also exhibited recurring incidences of major drought on the northern Great Plains. They too reported the cyclical behavior appeared to be synchronous with variations in solar irradiance. After making a case for "a direct connection between solar irradiance and weather and climate," they conclude "it seems reasonable that the cycles in aridity and eolian activity over the past several thousand years recorded in the sediments of lakes in the northern Great Plains might also have a solar connection."

Springer *et al*. (2008) derived a multidecadal-scale record of Holocene drought based on Sr/Ca ratios and $\delta^{13}C$ data obtained from stalagmite BCC-002 from Buckeye Creek Cave (BCC), West Virginia (USA) that "grew continuously from ~7000 years B.P. to ~800 years B.P." and then again "from ~800 years B.P. until its collection in 2002."

They identified seven significant mid- to late-Holocene droughts, six of which "correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle" (see Bond *et al*., 2001). In addition, they determined the Sr/Ca and $\delta^{13}C$ time series "display periodicities of ~200 and ~500 years and are coherent in those frequency bands." They also state, "the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle," and they "interpret the ~500-year periodicity to be a harmonic of the IRD oscillations." Noting "cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years," they observe "these latter values are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity." The five researchers conclude their findings "corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau *et al*., 2002; Willard *et al*., 2005; Denniston *et al*., 2007)," adding their high-resolution time series now provide even stronger evidence "in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results."

Mensing *et al*. (2004) inferred the hydrological history of the Pyramid Lake, Nevada area by analyzing a set of sediment cores for pollen and algal microfossils deposited in the lake over the past 7,630 years. According to the authors, "sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet," but "the past 2500 yr have been marked by recurring persistent droughts." The longest of these droughts, they found, "occurred between 2500 and 2000 cal yr B.P.," and others occurred "between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P." They note "the timing and magnitude of droughts identified in the pollen record compares favorably with previously published $\delta^{18}O$ data from Pyramid Lake" and with "the ages of submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada." They compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice (Bond *et al.,* 2001) and, like other researchers, found "nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record." Mensing *et al.* conclude "changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States]."

Asmerom *et al*. (2007) developed a high-resolution climate proxy for the southwest United States from $\delta^{18}O$ variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw $\delta^{18}O$ data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." They report cross-spectral analysis of the $\Delta^{14}C$ and $\delta^{18}O$ data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon), and this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

Hodell *et al*. (2001) analyzed sediment cores obtained from Lake Chichancanab on the Yucatan Peninsula of Mexico, reconstructing the climatic history of this region over the past 2,600 years. Long episodes of drought were noted throughout the record, and spectral analysis revealed a significant periodicity that matched well with a cosmic ray-produced ^{14}C

record preserved in tree rings believed to reflect variations in solar activity. They concluded "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

Black *et al*. (1999) found evidence of substantial decadal and centennial climate variability in a study of ocean sediments deposited in the southern Caribbean over the past 825 years. Their data suggest climate regime shifts are a natural aspect of Atlantic variability. They conclude "these shifts may play a role in triggering changes in the frequency and persistence of drought over North America." Because there was a strong correspondence between these phenomena and similar changes in ^{14}C production rate, they conclude "small changes in solar output may influence Atlantic variability on centennial time scales."

Helama *et al*. (2009) used regional curve standardization (RCS) procedures with data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland to develop what they describe as "the first European dendroclimatic precipitation reconstruction," which "covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP)," from AD 670 to AD 1993. They find "the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD." This interval, they write, "precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture." In addition, they report "the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930)."

The three Finnish scientists note the global medieval drought they discovered "occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook *et al*., 2004, 2007), eastern South America (Stine, 1994; Rein *et al*., 2004), and equatorial East Africa (Verschuren *et al*., 2000; Russell and Johnson, 2005a, 2007; Stager *et al*., 2005) between AD 900 and 1300." Noting this widespread evidence "argues for a common force behind the hydrological component of the MCA," they note "previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren *et al*., 2000; Stager *et al*., 2005) or the ENSO (Cook *et al*., 2004, 2007; Rein *et al*., 2004; Herweijer *et al*., 2006, 2007; Graham *et al*., 2007, Seager *et al*., 2007)," stating "the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the $\Delta^{14}C$ and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki *et al*., 2004)."

Verschuren *et al*. (2000) conducted a similar study of a small lake in Kenya, documenting the existence of three periods of prolonged dryness during the Little Ice Age that were, in their words, "more severe than any recorded drought of the twentieth century." They discovered all three of these severe drought events "were broadly coeval with phases of high solar radiation," as inferred from ^{14}C production data, "and the intervening periods of increased moisture were coeval with phases of low solar radiation." They concluded variations in solar activity "may have contributed to decade-scale rainfall variability in equatorial east Africa."

Also in Africa, working with three sediment cores extracted from Lake Edward (0°N, 30°E), Russell and Johnson (2005b) developed a continuous 5,400-year record of Mg concentration and isotopic composition of authigenic inorganic calcite as proxies for the lake's water balance, which is itself a proxy for regional drought conditions in equatorial Africa. They found "the geochemical record from Lake Edward demonstrates a consistent pattern of equatorial drought during both cold and warm phases of the North Atlantic's '1500-year cycle' during the late Holocene," noting similar "725-year climate cycles" are found in several records from the Indian and western Pacific Oceans and the South China Sea, citing the studies of von Rad *et al*. (1999), Wang *et al*. (1999), Russell *et al*. (2003), and Staubwasser *et al*. (2003). Russell and Johnson state their results "show that millennial-scale high-latitude climate events are linked to changes in equatorial terrestrial climate ... during the late Holocene" and "suggest a spatial footprint in the tropics for the '1500-year cycle' that may help to provide clues to discern the cycle's origin," noting there is reason to believe it may be solar-induced.

Garcin *et al*. (2007) explored hydrologic change using late-Holocene paleoenvironmental data derived from several undisturbed sediment cores retrieved from the deepest central part of Lake Masoko (9°20.0'S, 33°45.3'E), which occupies a maar crater in the Rungwe volcanic highlands of the western branch of Africa's Rift Valley, approximately 35 km north of Lake Malawi. According to the ten researchers, "magnetic, organic carbon, geochemical proxies and pollen assemblages indicate a dry climate during the 'Little Ice Age' (AD 1550–1850), confirming that the LIA in eastern Africa resulted in marked and synchronous hydrological changes," although "the direction of response varies between different African lakes."

They report "to the south (9.5-14.5°S), sediment cores from Lake Malawi have revealed similar climatic conditions (Owen *et al*., 1990; Johnson *et al*., 2001; Brown and Johnson, 2005)" "correlated with the dry period of Lakes Chilwa and Chiuta (Owen and Crossley, 1990)." They further note "lowstands have been also observed during the LIA at Lake Tanganyika ... from AD 1500 until AD 1580, and from ca. AD 1650 until the end of the 17th century, where the lowest lake-levels are inferred (Cohen *et al*., 1997; Alin and Cohen, 2003)." By contrast, they report "further north, evidence from Lakes Naivasha (0.7°S) and Victoria (2.5°S-0.5°N) indicates relatively wet conditions with high lake-levels during the LIA, interrupted by short drought periods (Verschuren *et al*., 2000; Verschuren, 2004; Stager *et al*., 2005)."

Garcin *et al*. also note, "inferred changes of the Masoko hydrology are positively correlated with the solar activity proxies." The African and French scientists say the Little Ice Age in Africa appears to have had a greater thermal amplitude than it did in the Northern Hemisphere, citing in support of this statement the paleoclimate studies of Bonnefille and Mohammed (1994), Karlén *et al*. (1999), Holmgren *et al*. (2001), and Thompson *et al*. (2002). Nevertheless, the more common defining parameter of the Little Ice Age in Africa was the moisture status of the continent, which appears to have manifested opposite directional trends in different latitudinal bands. In addition, the group of scientists emphasizes the positive correlation of Lake Masoko hydrology with various solar activity proxies "implies a forcing of solar activity on the atmospheric circulation and thus on the regional climate of this part of East Africa."

Trouet *et al*. (2009) describe in *Science* how they constructed a 947-year history (AD 1049–1995) of the North Atlantic Oscillation (NAO), using a tree-ring-based drought reconstruction for Morocco (Esper *et al*., 2007) and a speleothem-based precipitation proxy for Scotland (Proctor *et al*., 2000). This history begins in the midst of what they call the Medieval Climate Anomaly (MCA), "a period (~ AD 800-1300) marked by a wide range of changes in climate globally." This interval of medieval warmth, as they describe it, is "the most recent natural counterpart to modern warmth and can therefore be used to test characteristic patterns of natural versus anthropogenic forcing."

The results of their work are shown in Figure 3.5.1.1. The peak strength of the NAO during the MCA is shown to have been essentially equivalent to the peak strength the NAO has so far manifested during the Current Warm Period (CWP). This finding suggests the peak warmth of the MCA was also likely equivalent to the peak warmth of the CWP.

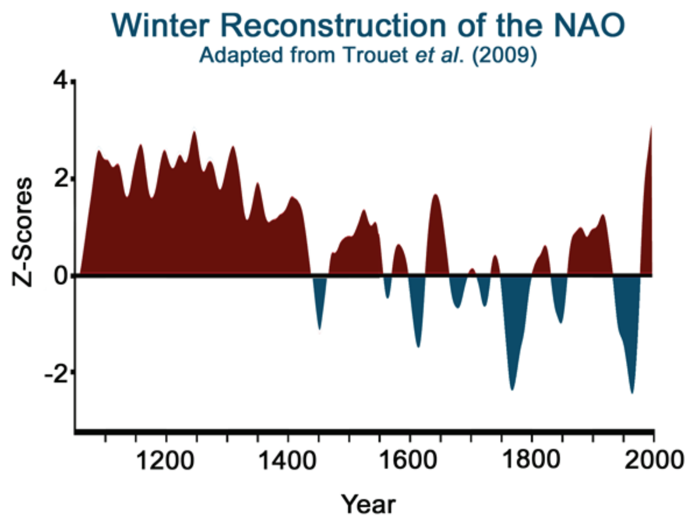

Figure 3.5.1.1. Winter reconstruction of the NAO for the period AD 1049-1995 based on a tree-ring-proxy drought reconstruction for Morocco and a speleothem-based precipitation proxy for Scotland. Adapted from Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* **324**: 78–80.

To explain their findings, Trouet *et al*. propose "the increased pressure difference between the Azores High and the Icelandic Low during positive NAO phases results in enhanced zonal flow, with stronger westerlies transporting warm air to the European continent," to which they add "stronger westerlies associated with a positive NAO phase may have enhanced the Atlantic meridional overturning circulation (AMOC)," which in turn may have generated "a related northward migration of the intertropical convergence zone." What initiated these phenomena? Trouet *et al*. write, "the persistent positive phase [of the NAO] reconstructed for the

MCA appears to be associated with prevailing La Niña-like conditions possibly initiated by enhanced solar irradiance and/or reduced volcanic activity and amplified and prolonged by enhanced AMOC."

Barker's (2008) analysis of data from 1876 to the present suggests when the Sun's South Pole is positive in the Hale Cycle, the likelihood of strongly positive and negative Southern Oscillation Index (SOI) values increase after certain phases in the cyclic ~22-year solar magnetic field. The SOI is also shown to track the pairing of sunspot cycles in ~88-year periods. This coupling of odd cycles—23–15, 21–13, and 19–11—produces an apparently close charting of positive and negative SOI fluctuations for each grouping. This Gleissberg effect is also apparent in the southern hemisphere rainfall anomaly. Over the past decade, the SOI and rainfall fluctuations have been tracking values similar to those recorded in Cycle 15 (1914–1924). This discovery may have important implications for future drought predictions in Australia and in countries in the Northern and Southern Hemisphere, which have been shown to be influenced by the sunspot cycle. Further, it provides a benchmark for long-term SOI behaviour.

There seems to be little question that variations in solar activity have been responsible for much of the drought variability of the Holocene in many parts of the world.

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3.5.2 Floods

The IPCC claims floods will become more variable and extreme as a result of CO_2-induced global warming. In Chapter 7 of this report, addressing extreme weather, we report peer-reviewed research showing modern flood frequency and severity fall well within the range of natural variability. Here we limit our examination once again to the issue of attribution, specifically investigating the influence of the Sun on floods.

We begin by reviewing what is known about the relationship of extreme weather events to climate in Europe during the Holocene. According to Starkel (2002), in general, more extreme fluvial activity, of both the erosional and depositional type, is associated with cooler climates. "Continuous rains and high-intensity downpours," writes Starkel, were most common during the Little Ice Age. Such "flood phases," the researcher reports, "were periods of very unstable weather and frequent extremes of various kinds." Starkel also notes "most of the phases of high frequency of extreme events during the Holocene coincide with the periods of declined solar activity."

In 2010, Markus Czymzik and colleagues published an important article on flooding in the journal of *Water Resources Research* (Czymik *et al.* 2010). The German and French scientists present the flood frequency development of Lake Ammersee (Bavaria's third largest lake) for the past 450 years. They observed an excellent correlation with solar activity as depicted in Figure 3.5.2.1. When solar activity was weak, flooding increased at Lake Ammersee. This relationship also was demonstrated in a February 2013 paper in *Quaternary Science Reviews* (Czymik *et al.* 2013).

Noren *et al*. (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km^2 region in Vermont and eastern New York (USA), after which several techniques were used to identify and date terrigenous in-wash layers depicting the frequency of storm-related floods. The analysis showed "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." Four major storminess peaks were identified, approximately 2.6, 5.8, 9.1, and 11.9 kyr ago, with the most recent upswing in storminess beginning "at about 600 yr BP [before present], coincident with the beginning of the Little Ice Age." Noren *et al*. state the pattern they observed "is consistent with long-term changes in the average sign of the Arctic Oscillation [AO]," further suggesting "changes in the AO, perhaps modulated by solar forcing, may explain a significant portion of Holocene climate variability in the North Atlantic region."

Schimmelmann *et al*. (2003) identified conspicuous gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, which they accurately dated by varve-counting. Analysis of the record revealed six prominent flood events occurring at approximately AD 212, 440, 603, 1029, 1418, and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200, and 1800. They further note "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells"; "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)"; and "the flood of ~AD 1418

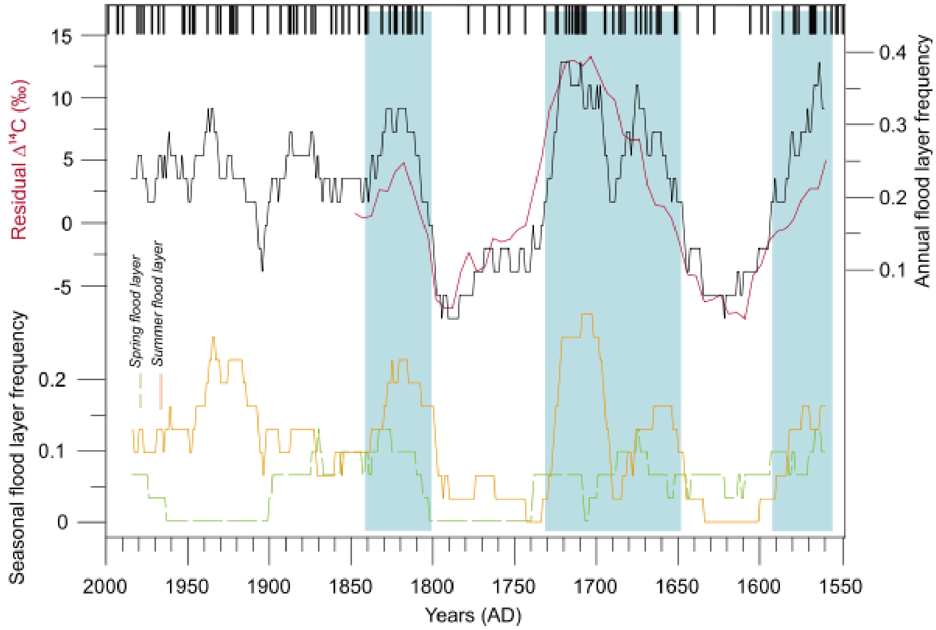

Figure 3.5.2.1. Flooding frequency of the Lake Ammersee region (bottom) and solar activity (above). Phases of minimal solar activity are shown with a blue shaded background. Whenever the sun was weak (high ^{14}C values, peak) flooding was more frequent. Reprinted with permission from Cyzmzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., and Brauer, A. 2010. A 450 year record of spring-summer flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 379-395, 10.1029/ 2009WR008360.

occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al*., 1997; Meeker and Mayewski, 2002)."

Schimmelmann *et al.* also note "the quasi-periodicity of ~200 years for southern California floods matches the ~200-year periodicities found in a variety of high-resolution palaeoclimate archives and, more importantly, a *c*.208-year cycle of solar activity and inferred changes in atmospheric circulation." They "hypothesize that solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years" and "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century."

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3.5.3 Monsoons

The IPCC's computer models fail to predict variability in monsoon weather, at least partly because they underestimate the Sun's role.

The Indian Summer Monsoon (ISM) and its associated local and regional patterns of rainfalls are among the most notoriously complex expressions of the tropical Earth's coupled land, ocean, and atmosphere system. The densely populated countries of South Asia depend critically on the rain water brought on by the ISM during the four summer months from June to September, which is why scientists are keenly interested in understanding the underlying factors responsible for the climatological and anomalous variations of the ISM rainfalls. They have identified a host of factors related to the ISM, from the quasi-biennial oscillation of the equatorial stratospheric winds, ENSO, Eurasian snow cover, conditions of the Indo-Pacific warm pool and Indian subcontinent, and sunspot activity. The pursuit of how the Sun's magnetic activity may modulate the ISM rainfall has been filled with many false starts and promises.

Figure 3.5.3.1 shows the surprising correlations between the All-India and Konkan-Goa regional rainfalls and the new solar forcing index of the derivative of the Total Solar Irradiance (TSI) reported in Agnihotri *et al.* (2011).

Noting many of the weaknesses in previous solar-ISM studies that adopted sunspot numbers or the 10.7 cm solar radio radiation flux, Agnihotri *et al.* (2011) adopt the time-derivative of TSI as a more relevant physical parameter for a better exploration of how the intrinsic solar radiative forcing of the Sun can modulate the ISM rainfall on multidecadal timescales. Van Loon and Meehl (2012) added further insights by arguing for the use of sunspot peaks as another useful metric for a physical investigation of solar-ISM relationship.

The results shown in Figure 3.5.3.1 suggest more severe drought conditions generally prevail during periods of steadily falling TSI or less solar radiation energy added to the Earth system. Periods of positive TSI derivative correspond to periods of anomalous excess of ISM rainfall, although the TSI derivative-rainfall relationship is clearly nonlinear and not fully symmetrical for solar-forcing-induced wet-dry oscillations and transitions.

Figure 3.5.3.2 adds more confidence to the empirical correlation of solar modulation of instrumental ISM rainfall shown in Figure 3.5.3.1 by extending the correlation back to 1700 AD, an additional 150 years of data record. Agnihotri *et al.* (2011) adopted the high-quality rainfall proxy data set obtained from the speleothem $\delta^{18}O$ data from Akalagavi cave located in the hills of the western Ghats mountain range in the southwestern state of Karnataka.

Figure 3.5.3.3 reveals a social dimension to the negative TSI derivative-related dry periods, severe drought, and even major famine (death toll greater than 1 million people) events recorded in all three data sets from instrumental, historical, and proxy records. The statistics from Figure 3.5.3.3 show four of seven major famines recorded in Indian subcontinent history fall near negative TSI derivatives. For example, the "terrible" famine of 1876–1879 that killed an estimated 10 million people (the death was not strictly from starvation alone; outbreaks of cholera were also a known factor) spread across nearly the whole of southern, western, and northern India and was associated with the most negative TSI derivative values constructed. The TSI derivative proxy is also able to pick up the famine events of 1896–1897 and 1899–1902 in which the estimated death tolls ranged from 8.4 to 19 million.

Agnihotri *et al.* (2011) attempted to explain the empirical correlations determined from real-world data (instrumental and proxy) by suggesting the differential addition or subtraction of solar energy to relatively cloud-free regions in the southern Indian ocean "would probably cause warm-pool sea surface conditions and atmospheric convective activity to vary in synchrony with the observed large-scale changes in the summer monsoonal circulation and rainfall in the Indian subcontinent." A positive (negative) TSI derivative phase corresponded to both enhanced (reduced) surface evaporation and an overall increase (decrease) in convective velocity, which in turns leads to the enhanced (reduced) southwest monsoonal circulation and increased (decreased) All-India and Konkan-Goa rainfalls, as observed in Figures 3.5.3.2 and 3.5.3.3.

Neff *et al*. (2001) investigated the relationship between a ^{14}C tree-ring record and a $\delta^{18}O$ proxy

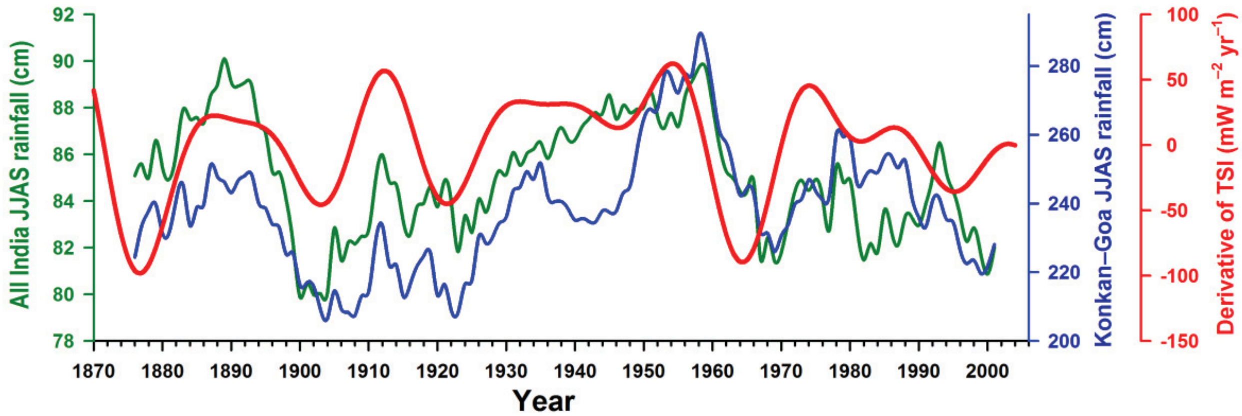

Figure 3.5.3.1. The All Indian Monsoon and Konkan-Goa Regional Monsoon rainfalls are correlated with the temporal derivative of the TSI offering new insights into a plausible solar modulation of the Indian summer monsoon rainfall variability on a multidecadal timescale. Reprinted with permission from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1980–1987.

record of monsoon rainfall intensity for the period 9,600–6,100 years before present, as recorded in calcite $\delta^{18}O$ data obtained from a stalagmite in northern Oman. The authors found the correlation between the two data sets to be "extremely strong," and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the $\delta^{18}O$ record and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Because variations in ^{14}C tree-ring records are generally attributed to variations in solar activity and intensity, and because this particular ^{14}C record was strongly correlated with the $\delta^{18}O$ record as well as the closely corresponding results of the spectral analyses, the authors conclude there is "solid evidence" that both signals (the ^{14}C and $\delta^{18}O$ records) are responding to solar forcing.

Similar findings were reported by Lim *et al.* (2005), who examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, creating a 6,500-year proxy record of major Asian dust events produced by northwesterly winter monsoonal winds that carry dust from the inner part of China all the way to Korea and the East China Sea. The Asian dust time series was found to contain both millennial- and centennial-scale periodicities; cross-spectral analysis between the EQC and a solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the researchers to conclude centennial-scale periodicities in the EQC could be ascribed primarily to fluctuations in solar activity.

Ji *et al*. (2005) used reflectance spectroscopy on a sediment core taken from Qinghai Lake in the northeastern part of the Qinghai-Tibet Plateau to construct a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. Monsoonal moisture since the late glacial period was shown to be subject to "continual and cyclic variations," including the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age, which lasted from 2,100 to 1,800 yr BP and 780 to 400 yr BP, respectively. Sandwiched between them was the warmer and wetter Medieval Warm Period, while preceding the DACP was the Roman Warm Period. Time series analysis of the sediment record revealed statistically significant periodicities (above the 95 percent level) of 123, 163, 200, and 293 years. The third of these periodicities corresponds well with the de Vries or Suess solar cycle, suggesting cyclical changes in solar activity are important triggers for some of the cyclical changes in monsoon moisture at Qinghai Lake.

Citing studies that suggest the Indian summer monsoon may be sensitive to changes in solar forcing of as little as 0.25 percent (Overpeck *et al*., 1996; Neff *et al*., 2001; Fleitmann *et al*., 2003), Gupta *et al*. (2005) compared trends in the Indian summer monsoon with trends in solar activity across the Holocene. Temporal trends in the Indian summer

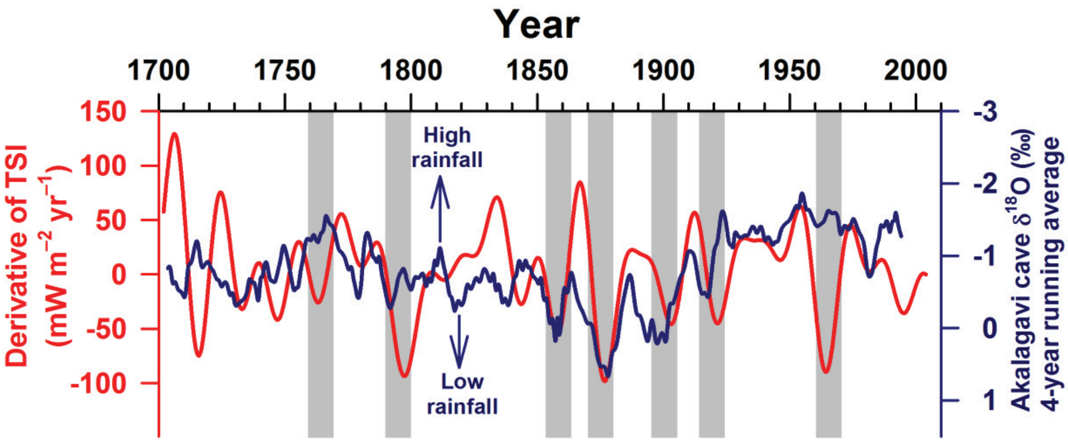

Figure 3.5.3.2. The solar modulation of the Indian summer monsoon rainfall variability on multidecadal timescale relation shown in Figure 3.5.3.1 above can be extended back to about 1700 AD using the rainfall proxy from Akalagavi Cave (located in southwestern India in the state of Karnataka) speleothem δ^{18}O data series. Adapted from Agnihotri, R., Dutta, K., and Soon, W. 2011. Temporal derivative of total solar irradiance and anomalous Indian summer monsoon: An empirical evidence for a sun-climate connection. *Journal of Atmospheric and Solar-Terrestrial Physics* **73**: 1980–1987.

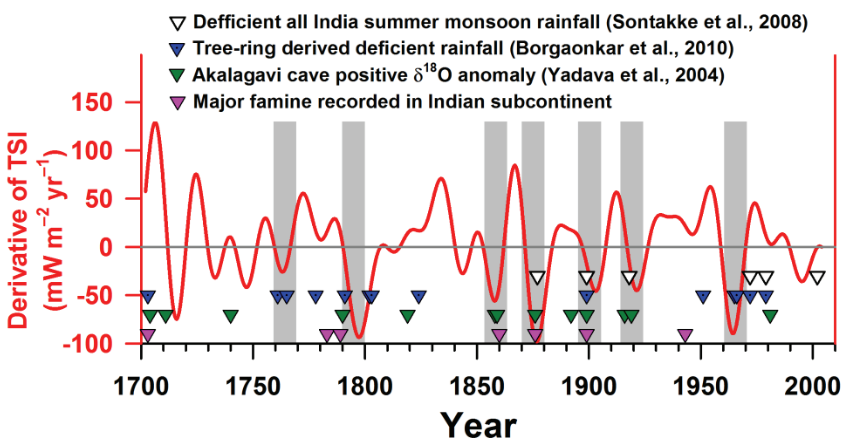

Figure 3.5.3.3. Major drought events from both instrumental and proxy datasets (both tree-ring and speleothem records) as well as major historical famine (death toll exceeding 1 million people) correspond roughly with intervals with low or most negative TSI derivatives (marked by gray vertical bars). Also adapted from Agnihotri *et al*. (2011).

monsoon were inferred from relative abundances of fossil shells of the planktic foraminifer *Globigerina bulloides* in sediments of the Oman margin, while temporal trends in solar variability were inferred from relative abundances of ^{14}C, ^{10}Be and haematite-stained grains.

Spectral analyses of the data sets revealed statistically significant periodicities in the *G. bulloides* time series centered at 1550, 152, 137, 114, 101, 89, 83, and 79 years; all but the first of these periodicities closely matched periodicities of sunspot numbers centered at 150, 132, 117, 104, 87, 82, and 75 years. Gupta *et al.* conclude this close correspondence provides strong evidence for a "century-scale relation between solar and summer monsoon variability." In addition, they report intervals of monsoon minima correspond to intervals of low sunspot numbers, increased production rates of the cosmogenic nuclides ^{14}C and ^{10}Be, and increased advection of drift ice in the North Atlantic, such that over the past 11,100 years "almost every multi-decadal to centennial scale decrease in summer monsoon strength is tied to a distinct interval of reduced solar output," and nearly every increase "coincides with elevated solar output," including a stronger monsoon (high solar activity) during the Medieval Warm Period and a weaker monsoon (low solar activity) during the Little Ice Age.

Gupta *et al*. consider the presence of the 1,550-year cycle in the Indian monsoon data to be "remarkable," as this cycle has been identified in numerous climate records of both the Holocene and the last glacial epoch (including Dansgaard/Oeschger cycles in the North Atlantic), strengthening the case for a Sun-monsoon-North Atlantic link. The researchers say they are "convinced" there is a direct solar influence on the Indian summer monsoon in which small changes in solar output bring about pronounced changes in tropical climate.

Khare and Nigam (2006) examined variations in angular-asymmetrical forms of benthic foraminifera and planktonic foraminiferal populations in a shallow-water sediment core obtained off Kawar (14°49'43"N, 73°59'37"E) on the central west coast of India, which receives heavy river discharge during the southwest monsoon season (June to September) from the Kali and Gangavali rivers. Down-core plots of the data showed three major troughs separated by intervening peaks, and "since angular-asymmetrical forms and planktonic foraminiferal population are directly proportional to salinity fluctuations," according to Khare and Nigam, "the troughs ... suggest low salinity (increased river discharge and thus more rainfall)," and "these wet phases are alternated by dry conditions." They further report the dry episodes of higher salinity occurred in AD 1320–1355, 1445–1535, and 1625–1660; the wet phases were centered at approximately AD 1410, 1590, and 1750, close to the ending of the sunspot minima of the Wolf Minima (AD 1280–1340), the Sporer Minima (AD 1420–1540), and the Maunder Minima (AD 1650–1710), respectively.

Although Khare and Nigam state "providing a causal mechanism is beyond the scope of the present study," they note "the occurrence of periods of enhanced monsoonal precipitation slightly after the termination of the Wolf, Sporer and Maunder minima periods (less Sun activity) and concomitant temperature changes could be a matter of further intense research." The correspondences seem to be more than merely coincidental, especially when the inferences of the two researchers are said to be "in agreement with the findings of earlier workers, who reported high lake levels from Mono Lake and Chad Lake in the vicinity of solar minima," as well as the Nile river in Africa, which "witnessed high level at around AD 1750 and AD 1575."

Tiwari *et al*. (2005) conducted a high-resolution (~50 years) oxygen isotope analysis of three species of planktonic foraminifera (*Globigerinoides ruber*, *Gs. Sacculifer,* and *Globarotalia menardii*) contained in a sediment core extracted from the eastern continental margin (12.6°N, 74.3°E) of the Arabian Sea, covering the past 13,000 years. Data for the final 1,200 years of this period were compared with the reconstructed total solar irradiance (TSI) record developed by Bard *et al*. (2000), based on fluctuations of ^{14}C and ^{10}Be production rates obtained from tree rings and polar ice sheets.

The researchers found the Asian Southwest Monsoon (SWM) "follows a dominant quasi periodicity of ~200 years, which is similar to that of the 200-year Suess solar cycle (Usokin *et al*., 2003)." This finding indicates, in their words, "that SWM intensity on a centennial scale is governed by variation in TSI," which "reinforces the earlier findings of Agnihotri *et al*. (2002) from elsewhere in the Arabian Sea."

In considering the SWM/TSI relationship, the five researchers note "variations in TSI (~0.2%) seem to be too small to perturb the SWM, unless assisted by some internal amplification mechanism with positive feedback," and they discuss two possible mechanisms. The first "involves heating of the Earth's stratosphere by increased absorption of solar ultraviolet (UV) radiation by ozone during periods of enhanced solar activity (Schneider, 2005)." According to this scenario, more UV reception leads to more ozone production in the stratosphere, which leads to more heat being transferred to the troposphere, which leads to enhanced evaporation from the oceans, which finally enhances monsoon winds and precipitation. The second mechanism, as they describe it, is that "during periods of higher solar activity, the flux of galactic cosmic rays to the Earth is reduced, providing less cloud condensation nuclei, resulting in less cloudiness (Schneider, 2005; Friis-Christensen and Svensmark, 1997)," which then allows for "extra heating of the troposphere" that "increases the evaporation from the oceans."

Dykoski *et al*. (2005) obtained high-resolution records of stable oxygen and carbon isotope ratios from a stalagmite recovered from Dongge Cave in southern China and developed a proxy history of Asian monsoon variability over the past 16,000 years. They discovered numerous centennial- and multidecadal-scale oscillations in the record up to half the amplitude of interstadial events of the last glacial age, indicating "significant climate variability characterizes the Holocene." Spectral analysis of $\delta^{14}C$ data revealed significant peaks at solar periodicities of 208, 86, and 11 years, which they say is "clear evidence that some of the variability in the monsoon can be explained by solar variability."

Building on this work and that of Yuan *et al*. (2004), Wang *et al*. (2005) developed a shorter (9,000-year) but higher-resolution (4.5-year) absolute-dated $\delta^{18}O$ monsoon record for the same location, which they compared with atmospheric ^{14}C data and climate records from lands surrounding the North Atlantic Ocean. Their monsoon record broadly followed summer insolation but was punctuated by eight significantly weaker monsoon periods lasting from one to five centuries, most of which coincided with North Atlantic ice-rafting events. In addition, they found "cross-correlation of the decadal- to centennial-scale monsoon record with the atmospheric ^{14}C record shows that some, but not all, of the monsoon variability at these frequencies results from changes in solar output," similar to "the relation observed in the record from a southern Oman stalagmite (Fleitmann *et al*., 2003)."

In a news item by Kerr (2005) accompanying the report of Wang *et al*., one of the report's authors (Hai Cheng of the University of Minnesota) was quoted as saying their study suggests "the intensity of the summer [East Asian] monsoon is affected by solar activity." Dominik Fleitman, who worked with the Oman stalagmite, also said "the correlation is very strong," stating it is probably the best monsoon record he had seen, "even better than ours." Gerald North of Texas A & M University, whom Kerr described as a "longtime doubter," admitted he found the monsoon's solar connection "very hard to refute," although he stated "the big mystery is that the solar signal should be too small to trigger anything."

Porter and Weijian (2006) used 18 radiocarbon-dated aeolian and paleosol profiles within a 1,500-km-long belt along the arid to semi-arid transition zone of north-central China to determine variations in the extent and strength of the East Asian summer monsoon throughout the Holocene. The dated paleosols and peat layers "represent intervals when the zone was dominated by a mild, moist summer monsoon climate that favored pedogenesis and peat accumulation," while "brief intervals of enhanced aeolian activity that resulted in the deposition of loess and aeolian sand were times when strengthened winter monsoon conditions produced a colder, drier climate."

The most recent of the episodic cold periods, which Porter and Weijian identify as the Little Ice Age, began about AD 1370, and the preceding cold period ended somewhere in the vicinity of AD 810. Consequently, their work implies the existence of a Medieval Warm Period that began sometime after AD 810 and ended some time before AD 1370. They also report the climatic variations they discovered "correlate closely with variations in North Atlantic drift-ice tracers that represent episodic advection of drift ice and cold polar surface water southward and eastward into warmer subpolar water." This correlation implies solar forcing (see Bond *et al*., 2001) as the most likely cause of the alternating multicentury mild/moist and cold/dry periods of North-Central China. Porter and Weijian's work thus helps establish the global extent of the Medieval Warm Period as well as its likely solar origin.

A 2009 study provides further evidence of relationships between solar controls and the Asian Monsoon. Based on carbonate percentages and ostracod abundances found in sediment cores they extracted from Hurleg Lake in the arid Qaidam Basin of the Northeast Tibetan Plateau, Zhao *et al*. (2009) developed a history of precipitation-driven changes in lake level over the past 1,700 years, which they compared with a contemporaneous history of tree-ring-derived precipitation over surrounding mountainous terrain as well as with changes in solar activity manifest in solar proxy residual $\Delta^{14}C$ data. The authors discovered "carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the last 1000 years," with the moisture pattern in the Qaidam Basin being "in opposite relation to tree-ring-based monsoon precipitations in the surrounding mountains, suggesting that topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region." In addition, they found cross-spectral analysis between their moisture proxies and the solar activity proxy "shows high coherence at the ~200-year periodicity which is similar to Chinese monsoon intensity records, implying the possible solar forcing of moisture oscillations in the NE Tibetan Plateau."

Zhao *et al*.'s work provides another example of cyclical solar activity controlling the cyclical nature of precipitation variations, wherein "higher solar output corresponds to a stronger monsoon, which intensifies the uplift of air mass on the high Tibetan Plateau and strengthens the subsidence of air mass over the Qaidam Basin," whereas "the reverse is true during the period of lower solar output," so that "high solar activity is correlated with dry climate in the Qaidam Basin and increased precipitation in monsoonal areas."

At this juncture, insights from the climate modeling effort can be instructive. In their study of centennial variations of global monsoon precipitation in the last millennium, Liu *et al.* (2009) called attention to the nonlinear responses in the climate model for a 0.2% increase in external solar forcing in triggering a 0.9% change in global monsoon precipitation, or an amplification factor of 4 to 5. Liu *et al.* explained the physical relation as follows:

> We argue that the effective radiative forcing-induced land-ocean thermal contrast causes an initial increase in monsoon precipitation. This initial increase is further reinforced by the increase in moisture supply because the warming induced by effective radiative heating tends to increase atmospheric moisture content. The increase in moisture supply can induce a positive feedback between the latent heat release (in precipitation) and monsoon flow convergence, thus further amplify the latent heat release, which may ultimately amplify the atmospheric circulation response. Therefore, the humidity feedback is a key amplifier linking solar irradiance and monsoon." (p. 2368)

In a study of the North American monsoon, Asmerom *et al*. (2007) developed a high-resolution climate proxy for the southwest United States in the form of $\delta^{18}O$ variations in a stalagmite found in Pink Panther Cave in the Guadalupe Mountains of New Mexico. Spectral analysis performed on the raw $\delta^{18}O$ data revealed significant peaks the researchers say "closely match previously reported periodicities in the ^{14}C content of the atmosphere, which have been attributed to periodicities in the solar cycle (Stuiver and Braziunas, 1993)." They report cross-spectral analysis of the $\Delta^{14}C$ and $\delta^{18}O$ data confirms the two records have matching periodicities at 1,533 years (the Bond cycle), 444 years, 170 years, 146 years, and 88 years (the Gleissberg cycle). In addition, they report periods of increased solar radiation correlate with periods of decreased rainfall in the southwestern United States (via changes in the North American monsoon); this behavior is just the opposite of what is observed with the Asian monsoon. These observations lead them to suggest the proposed solar link to Holocene climate operates "through changes in the Walker circulation and the Pacific Decadal Oscillation and El Niño-Southern Oscillation systems of the tropical Pacific Ocean."

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3.5.4 Streamflow

Streamflow is a climate variable related to precipitation, droughts, and floods. The studies reviewed here consider whether a significant solar influence on this variable.

Pederson *et al*. (2001) used tree-ring chronologies to reconstruct annual precipitation and streamflow histories in northeastern Mongolia over the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods revealed "variations over the recent period of instrumental data are not unusual relative to the prior record." The authors say the reconstructions "appear to show more frequent extended wet periods in more recent decades," but they note this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." The researchers also observe spectral analysis of the data revealed significant periodicities around 12 and 20–24 years, suggesting "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

In Western Europe, several researchers have studied precipitation histories of regions along the Danube River and their effects on river discharge, with some studies suggesting an anthropogenic signal present in the latter decades of the twentieth century is responsible for that period's drier conditions. Ducic (2005) analyzed observed and reconstructed river discharge rates near Orsova, Serbia over the period 1731–1990. He found the lowest five-year discharge value in the pre-instrumental era (period of occurrence: 1831–1835) was nearly equal to the lowest five-year discharge value in the instrumental era (period of occurrence: 1946–1950); the driest decade of the entire 260-year period was 1831–1840. Similarly, the highest five-year discharge value for the pre-instrumental era (period of occurrence: 1736–1740) was nearly equal to the five-year maximum discharge value for the instrumental era (period of occurrence: 1876–1880), differing by only 0.7 percent. The discharge rate for the last decade of the record (1981–1990), which prior researchers had claimed was anthropogenically influenced, was found to be "completely inside the limits of the whole series" and only slightly (38 m^3s^{-1} or 0.7 percent) less than the 260-year mean of 5356 m^3s^{-1}. In conclusion, Ducic states "modern discharge fluctuations do not point to [a] dominant anthropogenic influence"; further analysis suggests the detected cyclicity in the record may "point to the domination of the influence of solar activity."

Kondrashov *et al*. (2005) applied advanced spectral methods to fill in data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels on the Nile over the 1,300-year period AD 622 to 1922. They found several statistically significant periodicities, including cycles of 256, 64, 19, 12, 7, 4.2, and 2.2 years. Kondrashov *et al*. state the 4.2- and 2.2-year oscillations are likely the product of El Niño-Southern Oscillation variations, the 7-year cycle may be related to North Atlantic influences, and the longer-period oscillations may be due to solar-related forcings.

Mauas *et al*. (2008) note river streamflows "are excellent climatic indicators," especially in the case of rivers "with continental scale basins" that "smooth out local variations" and can thus "be particularly useful to study global forcing mechanisms." Focusing on South America's Parana River—the world's fifth largest in terms of drainage area and fourth largest with respect to streamflow—Mauas *et al*. analyzed streamflow data collected continuously on a daily basis since 1904. They report the detrended time series of the streamflow data were correlated with the detrended times series of both sunspot number and total solar irradiance, yielding Pearson's correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69, respectively, at "a significance level higher than 99.99% in both cases." This is strong evidence that solar variability, not manmade greenhouse gas emissions, was responsible for variation in Parana River streamflow during the modern industrial era.

A follow-up study by Mauas *et al*. (2011) analyzed river streamflows during the Little Ice Age. The authors write low water levels and low level in the flow of the Pirana River (and others) were found during a time of "unusual" minimum of solar activity, once again affirming the notion that solar activity induces significant variations in streamflow.

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3.6 Future Influences

Sunspot activity for Cycle 23 (from May 1996 until about 2008–2009) and the relatively slow and muted rising phase of Cycle 24 are unusual. This has heightened interest not only in solar magnetic field data but also more generally in the nature of the solar-climate connection. In concluding this chapter we examine recent research and scientists' thoughts on the potential influence of the Sun on Earth's future climate.

Livingston and Penn (2009) confirm "something is unusual about the current sunspot cycle," specifically "the current solar minimum has been unusually long." They note "with more than 670 days without sunspots through June 2009, the number of spotless days has not been equaled since 1933." In addition, they note, "the solar wind is reported to be in a uniquely low energy state since space measurements began nearly 40 years ago," citing the work of Fisk and Zhao (2009).

In 2006, Livingston and Penn reported the magnetic field strengths of sunspots "were decreasing with time, independent of the sunspot cycle" and "a simple linear extrapolation of those data suggested that sunspots might completely vanish by 2015." With several years' more data in hand, they report in 2009 "the predicted cycle-independent dearth in sunspot numbers has proven accurate," with sunspots still on track potentially to disappear in four to five years. That possibility led the two researchers to wonder openly whether their findings represent "an omen of long-term sunspot decline, analogous to the Maunder Minimum," the period 1645–1715 "when through several 11-year periods the Sun displayed few if any sunspots." They note "models of the Sun's irradiance suggest that the solar energy input to the Earth decreased during that time and that this change in solar activity could explain the low temperatures recorded in Europe during the Little Ice Age (Lean *et al*., 1992)."

The decline of the umbral magnetic field strength noted by Livingston and Penn and shown in Figure 3.6.1 (from Livingston *et al.* 2012, based on measurements for the near-infrared feature at Fe I 1565 nm) is not universally recognized. Pevtsov *et al.* (2011) found the sunspot field strengths (based on measurements for the visible line feature at Fe I 630 nm) tend to rise and wane with solar activity cycle; they do not detect a long-term decline of magnetic field strength. Rezaei *et al.* (2012), using more limited observations of 183 sunspots from the Tenerife Infrared Polarimeter, tend to support Pevtsov *et al*.

Nagovitsyn *et al.* (2012) offered a working explanation of the discrepancies between different observations and interpretations, noting opposing trends and dynamics in the largest and smallest sunspots. They write, "Suppose that during a grand solar minimum (e.g., Maunder minimum) the sunspots do not vanish all together, but only the large sunspots disappear. This change would not require the complete shutdown of the solar dynamo. Only the depth dependence of the dynamo will change, and it would favor the production of small sunspots." They point out "the smallest sunspots are much harder to detect, especially with the visual observations conducted with relatively poor telescopes, which could explain the low sunspot counts during some of the past grand minima."

Nagovitsyn *et al.* also point out, "modern observations suggest that the smaller sunspots are less likely to be associated with flare and coronal mass ejection activity, and thus, the magnetic fields on smaller scales may have a reduced effect on the amount of the magnetic field expelled to the heliosphere. The latter may affect the secondary proxies of the solar activity (e.g., cosmic-ray flux and frequency of aurorae) that are often used as additional identifiers of the Maunder minimum." They conclude, "this possibility that the grand minima in solar activity can be related to changes in size of sunspots produced by the dynamo should be explored further …"

Obridko *et al.* (2012) discussed the unusual sunspot minimum for Cycle 23 and what might be expected for the next several decades. They conclude, "after the high cycles of the twentieth century, the solar activity now turns to an average level [for Cycle 24] (rather than to a low one, as some authors believe), and only by the latter half of [the] twenty-first century we can wait for a great minimum of Dalton's type [i.e., 1790–1820]. The probability of a Maunder's type minimum [i.e., 1645–1715] is minimal."

The direct observations as updated in Livingston *et al.* (2012), however, do not rule out a highly muted future sunspot activity cycle. "By extrapolating our sunspot formation fraction to the predicted peak of Cycle 24 (in mid-2013) the sunspot formation fraction would be approaching 0.5 [i.e., a peak in the smoothed sunspot number of about 66–87 as estimated in Penn and Livingston 2011]," they write. "This suggests a rather small SSN for this cycle, in agreement with some recent Cycle 24 predictions."

Projecting further into the future, Livingston *et al.* note, "And while there is no physical mechanism which suggests that we should extrapolate further, it is fascinating to see that the sunspot formation fraction would be below 0.2 [i.e., a peak in the smoothed sunspot number of about 7–20 for Cycle 25 as estimated in Penn and Livingston 2011] by 2020. This would suggest that although magnetic flux would be erupting at solar surface during Cycle 25, only a small fraction of it would be strong enough to form visible sunspots or pores," as shown in Figure 3.6.2. "Such behavior would be highly unusual," they note, "since such a small solar maximum has not been observed since the Maunder Minimum."

In addition to the direct approach of studying the Sun itself, other researchers study the decadal, multidecadal, centennial, bicentennial, and even millennial periods in available climate and solar records in order to extrapolate solar activity into the future.

Solheim *et al*. (2012) point out Archibald (2008) was the first to recognize previous sunspot cycle length (PSCL) has a predictive power for temperature in the next sunspot cycle, if the raw (unsmoothed) value for the sunspot cycle length (SCL) is used, which Archibald demonstrated with data from de Bilt in the Netherlands; Hanover, New Hampshire, USA; Portland, Maine, USA; Providence, Rhode Island, USA; and Archangel, Russia.

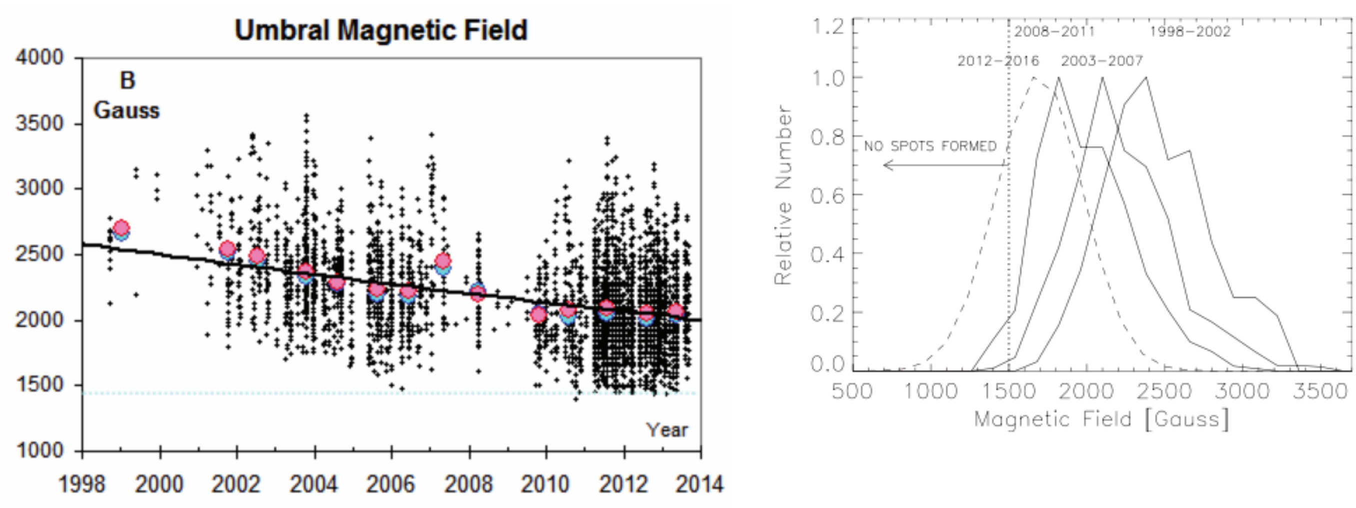

Figure 3.6.1. The measured sunspot umbral magnetic field strength from 1998 until April 2013 (left panel) and the distribution of the magnetic field strength for the same interval and the predicted distribution for 2012-2016 (right panel). It is predicted that a significant fraction of the magnetic fields will be below the threshold of 1500 G for the formation of sunspot. Adapted from Livingston, W., Penn, M.J., and Svalsgaard, L. 2012. Decreasing sunspot magnetic fields explain unique 10.7 cm radio flux. *The Astrophysical Journal Letters* **757**: L8. Left panel updated by Livingston in private correspondence, September 9, 2013.

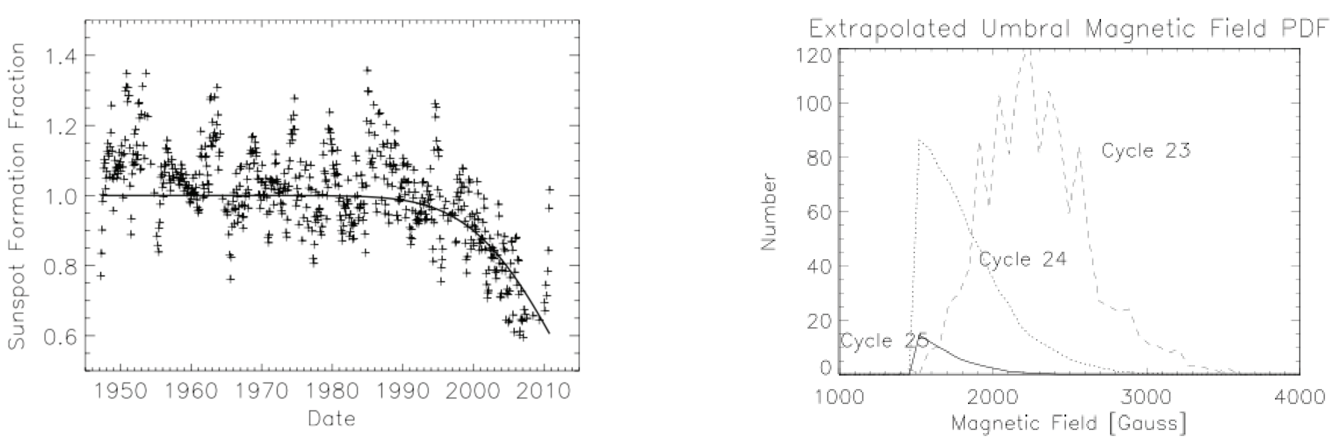

Figure 3.6.2. The history of the fraction of sunspot formation from about 1947 to present (left panel) illustrating the unusual nature of Cycles 23 and 24. The estimated distribution of sunspot magnetic field strengths for Cycle 23 contrasting those extrapolated for Cycles 24 and 25 (right panel). Left panel also adapted from Livingston *et al.* (2012). Right panel adapted from Penn, M.J. and Livingston, W. 2011. Long-term evolution of sunspot magnetic fields. In Choudhary, D.P. and Strassmeier, K.G. (Eds.) IAU Symposium No. 273, *The Physics of Sun and Star Spots*, (Cambridge: Cambridge University Press), pp. 126–133.

Solheim *et al*. further explored this relationship by comparing the raw SCL values and temperatures in the same and next sunspot cycles for a selection of weather stations in Norway and other European locations as well as sites across the North Atlantic region, including Armagh, Archangel, the Faroe Islands, Iceland, Svalbard and Greenland. The stations offered long weather records at places with small populations (to minimize urban heat island effects) in both coastal and inland locations.

The three Norwegian researchers found significant linear relationships between the average air temperature in a solar cycle and the length of the previous solar cycle for 12 of 13 weather stations in Norway and in the North Atlantic, as well as for 60 European stations and for the HadCRUT3N database. For Norway and the other European stations, they found "the solar contribution to the temperature variations in the period investigated is of the order 40%," while "an even higher contribution (63–72%) is found for stations at the Faroe Islands, Iceland and Svalbard," which they note is considerably "higher than the 7% attributed to the Sun for the global temperature rise in AR4 (IPCC, 2007)."

Solheim *et al*. say their findings imply "an annual average temperature drop of 0.9°C in the Northern Hemisphere during solar cycle 24," and "for the measuring stations south of 75°N, the temperature decline is of the order 1.0–1.8°C and may already have started." For Svalbard, they say "a temperature decline of 3.5°C is forecasted in solar cycle 24 for the yearly average temperature," and "an even higher temperature drop is forecasted in the winter months (Solheim *et al*., 2011)." They caution, "since solar forcing on climate is present on many timescales, we do not claim that our result gives a complete picture of the Sun's forcing on our planet's climate."

Ludecke *et al.* (2013) considered six periodic components with timescales greater than 30 years in the composite of a six-station temperature record from Central Europe since about 1757 AD, creating a very good reconstruction of the original instrumental records. They project a substantial cooling of the Central European temperature in the next one to two decades but caution their result "does not rule out a warming by anthropogenic influences such as an increase of atmospheric CO_2." The authors also note, "while … many indications point to the oscillations as intrinsic dynamics of the Earth, external causes for periodic dynamics cannot be ruled out."

The weak and delayed Cycle 24 surprised a number of solar experts, but not all of them. In 2003, a small group led by Mark Clilverd of the British Antarctic Survey in Cambridge had sensed something was amiss even before there were signs pointing to a slowdown in the Schwabe solar cycles (Clilverd *et al*., 2003). Clilverd *et al.* produced a solar activity forecast through 2140, which they further refined in 2006 (Clilverd *et al*., 2006). They predicted a strongly reduced Cycle 24 would mark the start of a solar activity slumber extending until the year 2030, at which time solar activity would pick up and remain at a more elevated level until 2100, after which another pronounced, extended quiet period would ensue. Their forecast was based on a careful analysis of the entire suite of known solar cycles, from the 11-year Schwabe Cycle to the 2,300-year Hallstatt Cycle. By extending these oscillations into the future, they correctly predicted the collapse in solar activity in Cycle 24 that followed a few years later.

In analyzing the global temperature data records (HadCRUT3 and HadCRUT4, respectively) directly, Loehle and Scafetta (2011) and Tung and Zhou (2013) conclude a large fraction of recent observed warming (60 percent over 1970–2000 and 40 percent over the past 50 years) can be accounted for by the natural upswing of the 60-year climatic cycle during its warming phase. Loehle and Scafetta (2011) proffer that "a 21st Century forecast suggests that climate may remain approximately steady until 2030–2040, and may at most warm 0.5–1.0°C by 2100 at the estimated 0.66°C/century anthropogenic warming rate, which is about 3.5 times smaller than the average 2.3°C/century anthropogenic warming rate projected by the IPCC up to the first decades of the 21st century. However, additional multisecular natural cycles may cool the climate further."

In an independent analysis of global temperature data from the Climatic Research Unit at the University of East Anglia and the Berkeley Earth Surface Temperature consortium, Courtillot *et al*. (2013) arrive at a new view of the significance of the ~60 yr oscillation. They interpret the 60-year period found in the global surface temperature records as "a series of ~30-yr long linear segments, with slope breaks (singularities) in ~1904, ~1940, and ~1974 (±3 yr), and a possible recent occurrence at the turn of the 21st century." Courtillot and his colleagues suggest "no further temperature increase, a dominantly negative PDO index and a decreasing AMO index might be expected for the next decade or two."

By extrapolating present solar cycle patterns into the future, several scientists have suggested a planetary cooling may be expected over the next few decades. The Gleissberg and Suess/de Vries cycles will reach their low points between 2020 and 2040 at a level comparable to what was experienced during the Dalton Minimum. At that time, around 1790–1820, global temperatures were nearly 1°C lower than they are today; conservatively, at least half of that cooling was due to a weaker Sun.

Moreover, the Pacific Decadal Oscillation (PDO) is expected to be in a cool phase by 2035, and the Atlantic Multidecadal Oscillation (AMO) will begin to drop around 2020. Such internal climate cycles are generally responsible for about 0.2 to 0.3°C of the temperature dynamic.

By calibrating the natural climate cycles to the documented geological data series of the past, we can project a total cooling contribution from these natural climate forcings of 0.4 to 0.6°C by the year 2035 as compared to today. Such cooling might be masked to some extent by anthropogenic effects, such as greenhouse gases, urbanization, and land-use change. Only time will tell whether such interpolations of future climate are correct, but given the stagnant temperatures experienced over the past decade, the odds may favor the Sun.

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4

Observations: Temperature Records

Sherwood Idso (USA)

Craig Idso (USA)

Contributing: S. Fred Singer (USA), Ross McKitrick (Canada), Roy Spencer (USA)

Key Findings

Introduction

4.1 Global Temperature Records
4.1.1 Cause of Late Twentieth Century Warming
4.1.2 Urbanization Taints Modern Records
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4.2 The Non-Uniqueness of Current Temperatures
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Key Findings

The following bulleted points summarize the main findings of this chapter:

- The Intergovernmental Panel on Climate Change (IPCC) contends the warming of the past half-century is unprecedented in the past millennium and anthropogenic in origin. In contrast, based upon the evidence presented here and in other chapters of this volume, the Nongovernmental International Panel on Climate Change (NIPCC) concludes natural variability is responsible for late twentieth century warming and the cessation of warming since 1998. The modern rise of carbon dioxide and other atmospheric greenhouse gases has had little, if any, measurable effect on twentieth century climate.

- Filtering out urbanization and related land-use effects in the temperature record is a complicated task, and there is solid evidence the methods currently used are inadequate. Urbanization may account for a larger portion of the modern temperature rise than the IPCC acknowledges.

- Surface-based temperature histories of the globe almost certainly contain a significant warming bias introduced by insufficient corrections for the non-greenhouse-gas-induced urban heat island effect. It may be next to impossible to make proper corrections for this deficiency, as the urban heat island of even small towns dwarfs any concomitant augmented greenhouse effect that may be present.

- The IPCC claim of robust evidence of amplified CO_2-induced warming in Earth's polar regions is patently false, having been invalidated time and again by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies in Earth's polar regions demonstrate the atmosphere's CO_2 concentration is not a major player in bringing about significant changes in Earth's climate.

- Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration, revealing the true inability of carbon dioxide to drive climate change throughout the Holocene. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades and centuries even though the atmosphere's CO_2 concentration remained approximately 30 percent lower than it is today.

- The IPCC concludes "there is high confidence that the Medieval Climate Anomaly was not characterized by a pattern of higher temperatures that were consistent across seasons and regions" (p. 5–4 of the Second Order Draft of AR5, dated October 5, 2012). Quite to the contrary, an enormous body of literature clearly demonstrates the IPCC's assessment of the Medieval Climate Anomaly (MCA) is incorrect. The degree of warming and climatic influence during the MCA indeed varied from region to region, and hence its consequences were manifested in a variety of ways. But literally hundreds of peer-reviewed scientific articles confirm it occurred and was a global phenomenon.

- Computer model simulations have given rise to three claims regarding the influence of global warming on ENSO events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. Observational data do not agree with the models' claims: In nearly all historical records, frequent and strong El Niño activity increases during periods of colder temperatures (e.g., the Little Ice Age) and decreases during warm ones (e.g., Medieval Warm Period, Current Warm Period).

Introduction

In its current and prior assessment reports the IPCC makes clear its position that the past few decades were the warmest of the past hundred years on the planet, and possibly of the entire past millennium. Their statements on this topic include:

> Starting in the 1980s each decade has been significantly warmer than all preceding decades. … All ten of the warmest years have occurred since 1997, with 2010 and 2005 effectively tied for the warmest year on record (Second Order Draft of AR5, dated October 5, 2012, p. 2–33).
>
> Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years (Summary for Policy Makers, Fourth Assessment Report, p. 9).
>
> Better understanding of pre-instrumental data shows that warming since the mid-20th century is far outside the range of internal climate variability estimated from such records (Second Order Draft of AR5, dated October 5, 2012, p. 10-3).

The IPCC further asserts the supposedly unprecedented high air temperatures of the present are largely the consequence of increasing anthropogenic CO_2 emissions resulting from the burning of fossil fuels, claiming:

> It is *very unlikely* that reconstructed temperatures since 1400 can be explained by natural internal variability alone. Climate model simulations that include only natural forcings can explain a substantial part of the pre-industrial inter-decadal temperature variability since 1400 on hemispheric scales. However such simulations fail to explain more recent warming since 1950 without the inclusion of anthropogenic increases in greenhouse gas concentrations. The warming since 1950 is far outside the range of similar length trends estimated in residual internal variability estimated from reconstructions of the past millennium (Second Order Draft of AR5, dated October 5, 2012, p. 10-5).
>
> We conclude it is *extremely likely* that human activities have caused most of (at least 50%) the observed increase in global average temperatures since the 1950s and that it is *virtually certain* that this warming is not due to internal variability alone (Second Order Draft of AR5, dated October 5, 2012, p. 10-3)

These two most basic assertions of the IPCC—that the warming of the past half century is unprecedented in the past millennium and anthropogenic in origin—serve as the foundation of nearly all of the work conducted by the IPCC. These assertions are the basic building blocks upon which politicians and governments have sought to radically reformulate the energy basis of the industrialized world to avoid a host of climatic consequences they insist will occur (or are occurring) as temperatures continue to rise.

The present chapter examines these two temperature-related claims and finds the IPCC's assertions are based on a limited and narrow interpretation of the available scientific literature. Many published studies, for example, question the accuracy of the surface temperature record, collectively demonstrating the datasets upheld by the IPCC likely overestimate the warming that has occurred over the past half-century. In addition, the publication of many historical paleoclimate records reveal there is nothing unusual, unnatural, or unprecedented about the current level of planetary warmth. These facts, coupled with the problems inherent in climate models (Chapter 1 of this volume), the failure of the models to properly account for and incorporate important forcings and feedbacks into their model runs (Chapters 2 and 3), and the array of real-world observations that run counter to the model projections with respect to various climate and other related phenomena (this chapter and Chapters 5, 6, and 7), all demonstrate the IPCC is premature—if not flat-out wrong—in attributing recent warming to anthropogenic CO_2 emissions.

4.1 Global Temperature Records

4.1.1 Discerning the Cause of Late Twentieth Century Global Warming

The IPCC has concluded it is "*extremely likely*" the anthropogenic release of greenhouse gases into the atmosphere has caused most of the increase in global average temperature they claim has been observed since the 1950s.

In brief, the reason for the IPCC's confidence stems from comparisons of global climate model runs of the twentieth century using natural forcings and natural *plus* anthropogenic forcings. When the models are run throughout the twentieth century using natural forcings alone, they are unable to reproduce the rise seen in various global temperature datasets. When they are run with the added anthropogenic forcing due to CO_2 and other greenhouse gases, there is relatively good agreement between the model projections and temperature observations. Thus, the IPCC attributes the mid- to late-twentieth century observational warming to rising greenhouse gases.

In making this attribution, however, the IPCC makes several assumptions. First, it assumes the magnitude of the mid- to late-twentieth century rise in temperature, as presented in the global land and ocean datasets, is robust. (It is not; see Section 4.1.2.) Second, the IPCC assumes the models are using an accurate temperature sensitivity to represent the modern rise in greenhouse gases. (They are not; see Chapter 1.1.5.) Third, the IPCC assumes the models correctly capture and portray each of the important processes that affect climate. (They do not; see Chapters 1, 2, and 3.) Fourth, the IPCC assumes the models correctly depict and account for natural variability. (They do not, as evidenced by material presented in all chapters of this volume.)

With respect to the first assumption, a number of difficulties are encountered in obtaining accurate global temperature measurements and assembling them into aggregate histories of global climate change over the era of modern instrumentation. These difficulties, if not properly addressed, can induce significant errors into the global temperature record. The magnitude of these errors in many instances has been reported to be as large as or larger than the anthropogenic signal anticipated by the IPCC to be residing in such datasets.

Among such potential errors are temporal changes in microclimate surrounding temperature measurement sites, such as urbanization, which often go unrecognized or for which insufficient adjustments are made; long-term degradation of the shelters that house the temperature-measuring equipment, such as the shelters' white paint becoming less reflective and their louvers partially obstructed; changes in what is actually being measured, such as true daily maximum and minimum temperatures or temperatures at specified times of day; changes in measurement devices and ways of accessing the data, such as changing from having to open the shelter door to read the temperature, as was done in earlier days, to not having to do so, due to the automatic recording of the data, as has become commonplace in more recent times; general station degradation and many station closures over time; the changing and uneven geographical representation of the surface temperature network; poor attention to careful acquisition of data in many parts of the world; and numerous problems associated with obtaining a correct and geographically complete record of surface air temperature over the 70 percent of the globe that is covered by oceans.

Arguably the most serious of the potential inaccuracies is that related to urbanization, addressed in more detail in Section 4.1.2. As demonstrated there, the impact of population growth on the urban heat island effect is very real and can be very large, vastly overshadowing the effects of natural temperature change. Towns with as few as a thousand inhabitants, for example, typically create a warming of the air within them that is more than twice as great as the increase in mean global air temperature presumed to have occurred since the end of the Little Ice Age. Urban heat islands of the great metropolises of the world are much larger, creating warmings that rival those that occur between full-fledged ice ages and interglacials. Given the potential of this phenomenon to introduce errors of such magnitude into the temperature records of the past century, it is surprising the IPCC is mostly dismissive of this topic and its significance in its *Fifth Assessment Report*.

Other observations also point to problems with the global surface air temperature record. The satellite microwave-sounding-unit temperature record shows less warming when compared with surface temperature records since coming online in 1979, and the weather-balloon temperature record also shows less warming than the surface temperature records since the 1940s.

The second major assumption made by the IPCC in attributing the late twentieth century rise in temperature to the modern rise in atmospheric greenhouse gases pertains to climate sensitivity. Most models use a climate sensitivity in which global temperatures rise between 1.5 and 4.5°C in response to a doubling of the atmosphere's CO_2 concentration. However, as discussed in Chapter 1.1.5, these values could be as much as a factor of ten too high compared to what actually occurs in nature.

A simple test demonstrating the IPCC's faulty assessment of climate sensitivity was performed a little over a decade ago by Stanhill (2001), who examined the relationship between temperature and CO_2 over the prior 140 years. In describing the character of the global surface temperature record over this period, he said it can be broken into four parts, beginning with "a long and very irregular but generally cool first period between 1860 and 1910, followed by a very rapid, regular and prolonged period of global warming between 1910 and 1943, succeeded by an equally long period of small and irregular cooling from 1943 to 1975 and, since then, the current warming period," which latter warming stopped about the time of Stanhill's writing, revealing no statistical trend in the temperature data since 1998.

During the prolonged period of global warming in the early part of the past century, Stanhill notes, "the rate of anthropogenic releases of radiatively active gasses, the presumed cause of the current global warming, was approximately one tenth of that in the present warming period," the temperature increase of which "has been shorter, more irregular and less rapid than the earlier warming." The order-of-magnitude-greater release of greenhouse gases since 1975 has not produced a warming as dramatic as the one that occurred in the early part of the century that was coeval with the release of but one-tenth as much CO_2 and other greenhouse gases. There is thus little reason to put much credence in the IPCC's estimates on climate sensitivity. This point is further driven home in Chapter 1.1.1, where several additional examples from the peer-reviewed literature are cited to show climate is relatively insensitive to changes in CO_2, and CO_2 is a *follower* of temperature change as opposed to an *initiator* of it.

The third major assumption the IPCC makes in attributing the late twentieth century rise in temperature to the modern rise in atmospheric greenhouse gases is that the models correctly capture and portray each of the important processes that affect climate. Chapter 1 of this volume presents an in-depth discussion of the inner workings and limitations of climate models.

Climate models are important tools used to advance our understanding of current and past climate. They provide qualitative and quantitative information about potential future climate. But in spite of their sophistication, they remain only *models*. They represent simulations of the real world, constrained by their ability to correctly capture and portray each of the important processes that operate to affect climate. Chapter 1 demonstrates the models remain deficient in many aspects of their portrayal of the climate, which reduces their ability to provide reliable simulations of the future.

Confidence in a model is further based on the careful evaluation of its performance. Just because one, two, or several models agree on a particular outcome, such agreement is not sufficient grounds to conclude the model projections are robust, for the model projections must be validated against real-world observations at the appropriate temporal and spatial scales. Without such a comparison, the true performance of a model cannot be verified.

A large portion of this volume, therefore, is devoted to the evaluation of climate model projections against real-world climate and other biospheric data, including material from this chapter. That evaluation, summarized in the findings of numerous peer-reviewed scientific papers, reveals the models consistently fail to accurately simulate important components of the Earth-atmosphere-ocean system.

Climate models predict a unique anthropogenic "fingerprint" of CO_2-induced global warming in which there is a warming trend in the tropical troposphere that increases with altitude (see Figure 4.1.1.1.) The models further suggest climate changes due to solar variability or other known natural factors do not yield this pattern, whereas sustained greenhouse warming does.

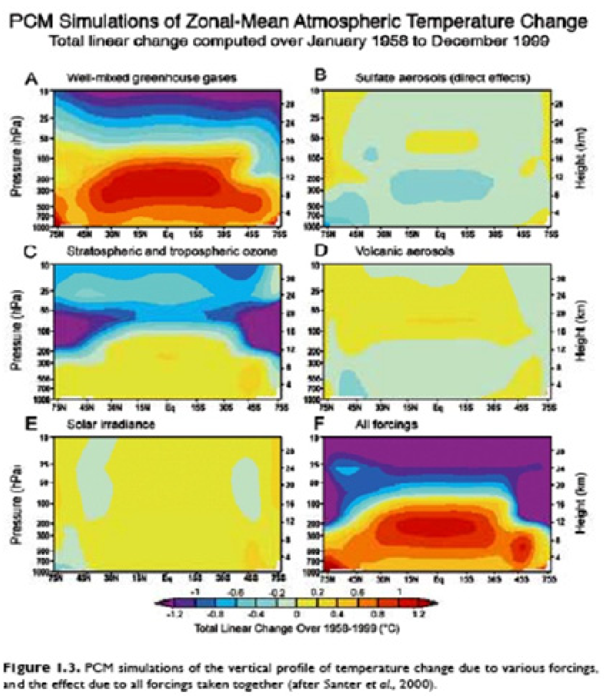

Figure 4.1.1.1. Model-calculated zonal mean atmospheric temperature change from 1890 to 1999 (degrees C per century) as simulated by climate models from [A] well-mixed greenhouse gases, [B] sulfate aerosols (direct effects only), [C] stratospheric and tropospheric ozone, [D] volcanic aerosols, [E] solar irradiance, and [F] all forcings (U.S. Climate Change Science Program 2006, p. 22). Note the pronounced increase in warming trend with altitude in figures A and F, which the IPCC identified as the 'fingerprint' of greenhouse forcing.

The comparison of these projections with observations was first attempted in the IPCC's *Second Assessment Report* (SAR) (IPCC-SAR, 1996, p. 411). Its Chapter 8, titled "Detection and Attribution," attributed observed temperature changes to anthropogenic factors: greenhouse gases and aerosols. The attempted match of warming trends with altitude turned out to be spurious, since it depended entirely on a particular choice of time interval for the comparison (Michaels and Knappenberger, 1996). Similarly, an attempt to correlate the observed and calculated geographic distribution of surface temperature trends (Santer *et al.* 1996) involved making changes on a published graph that could and did mislead readers (Singer, 1999, p. 9; Singer, 2000, pp. 15, 43–44). In spite of these shortcomings, IPCC-SAR concluded the data matched the observations and "the balance of evidence" therefore supported anthropogenic global warming.

With the availability of higher-quality temperature data, especially from balloons and satellites, and with improved models, it has become possible to make this comparison in a more realistic way. This was done in a report issued by the U.S. Climate Change Science Program (CCSP) in April 2006, making it readily available to the IPCC for its *Fourth Assessment Report*. It permits a more realistic comparison of the data (Karl *et al.,* 2006).

The CCSP report is an outgrowth of a National Academy of Scienses (NAS) report, "Reconciling Observations of Global Temperature Change," issued in January 2000 (NAS, 2000). The NAS report compared surface and troposphere temperature trends and concluded they cannot be reconciled. Six years later, the CCSP report expanded considerably on the NAS study. It was essentially a specialized report addressing the most crucial issue in the global warming debate: Is current global warming anthropogenic or natural? The CCSP findings were unequivocal. Although all greenhouse models show an increasing warming trend with altitude, peaking around 10 km at roughly two times the surface value, the temperature data from balloons give the opposite result: no increasing warming, but rather a slight cooling with altitude in the tropical zone. See Figures 4.1.1.2 and 4.1.1.3, reproduced directly from the CCSP report.

The CCSP executive summary inexplicably claims agreement between observed and calculated patterns, the opposite of what the report itself documents. It tries to dismiss the obvious disagreement shown in the body of the report by suggesting there might be something wrong with balloon and satellite data instead of the model projections. Unfortunately, many people do not read

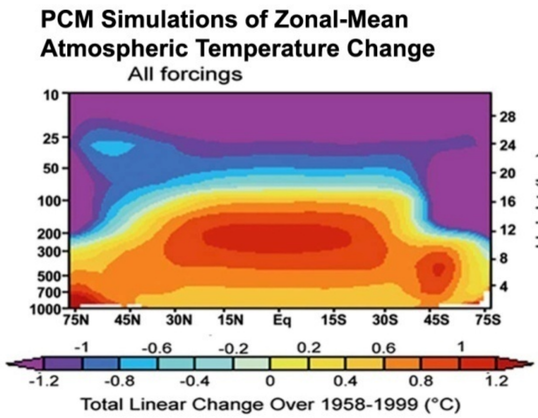

Figure 4.1.1.2. Greenhouse-model-predicted temperature trends versus latitude and altitude; this is figure 1.3F from CCSP 2006, p. 25. Note the increased temperature trends in the tropical mid-troposphere, in agreement also with the IPCC result (IPCC-AR4 2007, p. 675).

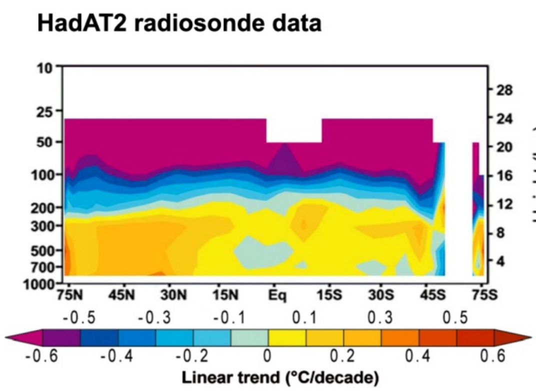

Figure 4.1.1.3. By contrast, observed temperature trends versus latitude and altitude; this is figure 5.7E from CCSP 2006, p. 116. These trends are based on the analysis of radiosonde data by the Hadley Centre and are in good agreement with the corresponding U.S. analyses. Notice the absence of increased temperature trends in the tropical mid-troposphere.

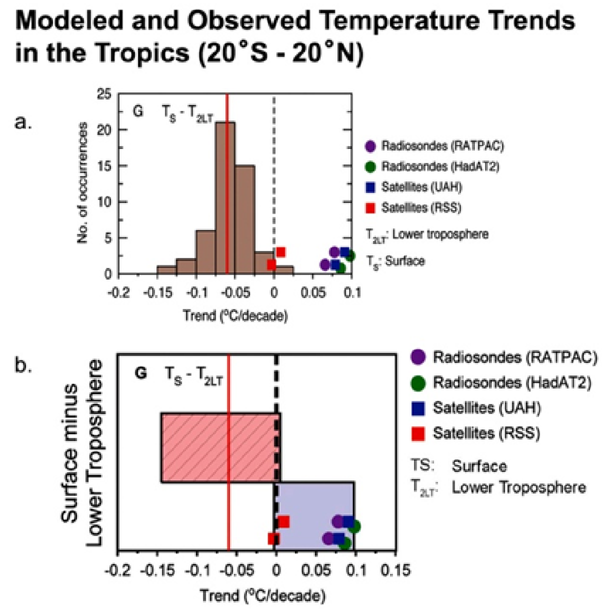

Figure 4.1.1.4a. Another way of presenting the difference between temperature trends of surface and lower troposphere; this is figure 5.4G from CCSP 2006, p. 111. The model results show a spread of values (histogram); the data points show balloon and satellite trend values. Note that the model results hardly overlap with the actual observed trends. (The apparent deviation of the RSS analysis of the satellite data is as yet unexplained.)

Figure 4.1.1.4b. By contrast, the executive summary of the CCSP report presents the same information as Figure 4.2.1.4a in terms of "range" and shows a slight overlap between modeled and observed temperature trends (Figure 4G, p. 13). However, the use of "range" is clearly inappropriate (Douglass et al. 2007) because it gives undue weight to outliers.

beyond the summary and have therefore been misled to believe the CCSP report supports anthropogenic warming. It does not.

The same information also can be expressed by plotting the difference between surface trend and troposphere trend for the models and for the data (Singer, 2001). As seen in Figure 4.1.1.4a and 4.1.1.4b, the models show a histogram of negative values (i.e., surface trend less than troposphere trend) indicating atmospheric warming will be greater than surface warming. By contrast, the data show mainly positive values for the difference in trends, demonstrating measured warming is occurring principally on the surface and not in the atmosphere.

The same information can be expressed in yet a different way, as seen in research papers by Douglass *et al.* (2004, 2007), as shown in Figure 4.1.1.5. The models show an increase in temperature trend with altitude, but the observations show the opposite.

This mismatch of observed and modeled warming of the tropical troposphere has been upheld most recently by Singer (2013), and this incongruity between model projection and data observations clearly falsifies the model output. The IPCC seems to be aware of this contrary evidence but has tried to ignore it or wish it away. The summary for policymakers of IPCC's *Fourth Assessment Report* (IPCC 2007-I, p. 5) distorts the key result of the

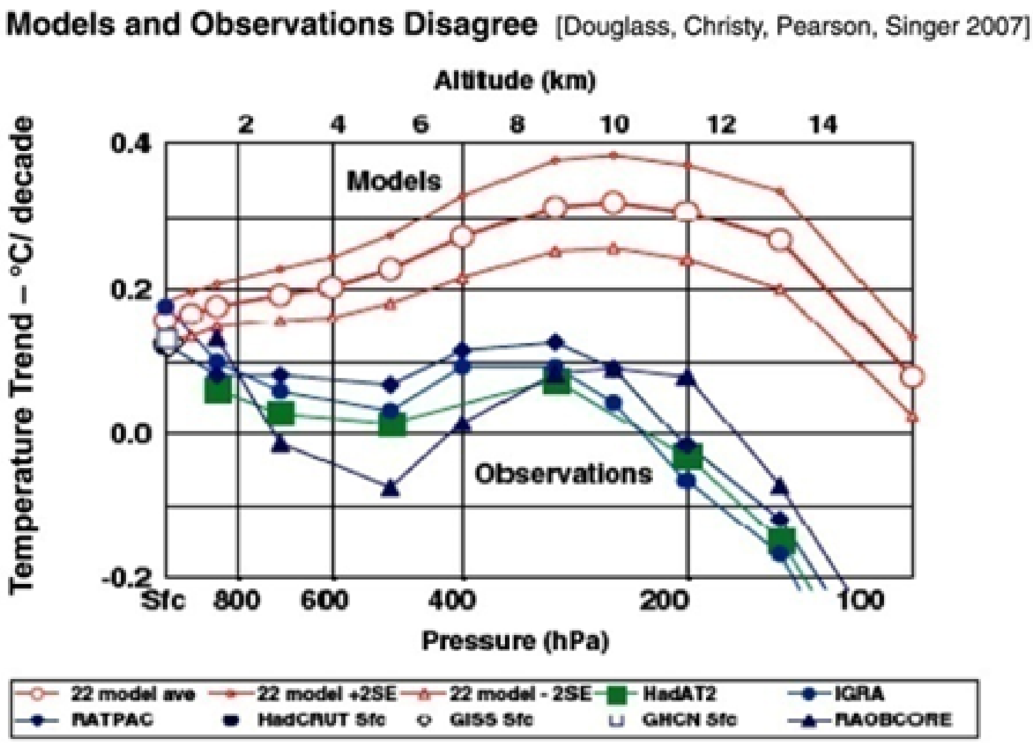

Figure 4.1.1.5. A more detailed view of the disparity of temperature trends is given in this plot of trends (in degrees C/decade) versus altitude in the tropics. Models show an increase in the warming trend with altitude, but balloon and satellite observations do not. Adapted from Douglass, D.H., Christy, J.R., Pearson, B.D., and Singer, S.F. 2007. A comparison of tropical temperature trends with model predictions. *International Journal of Climatology* (Royal Meteorological Society). DOI:10.1002/joc.1651.

CCSP report: "New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record, and are consistent within their respective uncertainties, largely reconciling a discrepancy noted in the TAR." How is this possible? It is done partly by using the concept of "range" instead of the statistical distribution shown in Figure 4.1.1.4a. But "range" is not a robust statistical measure because it gives undue weight to "outlier" results. If robust probability distributions were used, they would show an exceedingly low probability of any overlap of the modeled and observed temperature trends.

If one takes greenhouse model results seriously, the greenhouse fingerprint would suggest the true surface trend should be only 30 to 50 percent of the observed balloon/satellite trends in the troposphere. In that case, one would end up with a much-reduced surface warming trend, an insignificant anthropogenic effect, and a minor greenhouse-induced warming in the future.

While discussing other important failures in model performance, Spencer (2013) also highlights this model vs. observation discrepancy of temperatures in the tropical troposphere. In written testimony before the U.S. Senate Environment and Public Works Committee, he notes "the only truly global temperature measurements, unaffected by artifacts such as urban heat island effects, are for the bulk atmosphere from Earth-orbiting satellites," adding, "all other measurements are at points and so are geographically incomplete."

The composite satellite record of temperature anomalies of the lower troposphere is presented in Figure 4.1.1.6. Spencer discusses several significant features elucidated by this record:

1. The magnitude of global-average atmospheric warming between 1979 and 2012 is only about

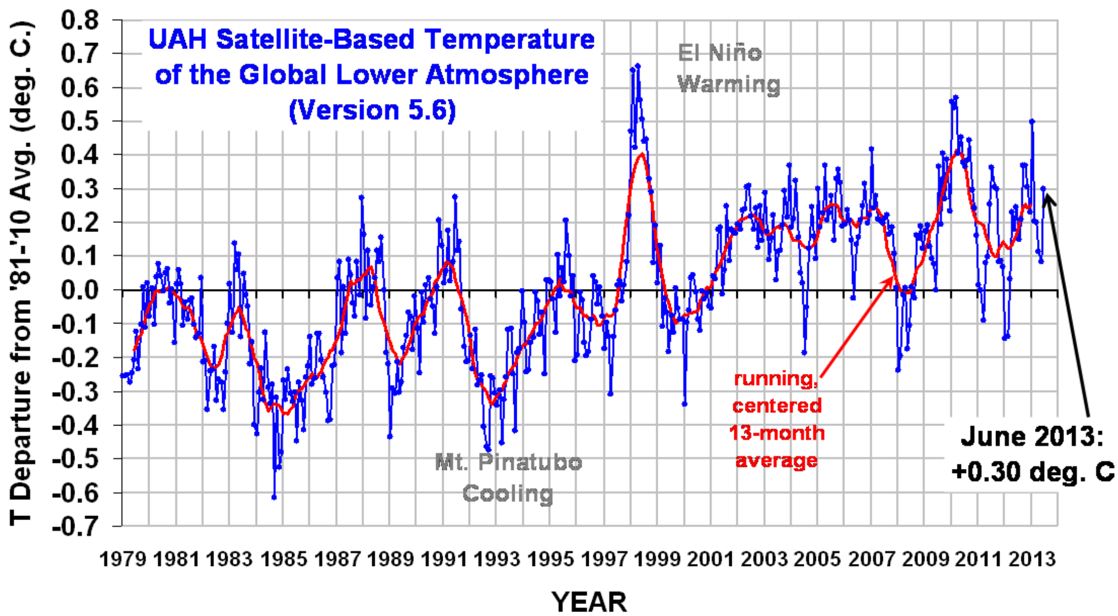

Figure 4.1.1.6. UAH global lower tropospheric (LT) temperature variations between January 1979 and June 2013. Adapted from Spencer, R.W. 2013. Statement to the U.S. Senate Environment and Public Works Committee, 19 July 2013, Washington, DC.

50% that predicted by the climate models relied upon by the IPCC in their projections of global warming.

2. The level of warming in the most recent 15 year period is not significantly different from zero, despite this being the period of greatest greenhouse gas concentration. This is in stark contrast to claims that warming is "accelerating."

3. The level of observed tropical atmospheric warming since 1979 is dramatically different from that predicted by climate models; it is below the projections of all 73 models we have analyzed (see Figure 4.1.1.7).

With respect to his third point, Spencer provides a graph of mid-tropospheric temperature variations for the tropics (20°N to 20°S) in 73 current (CMIP5) climate models versus measurements made from two satellite and four weather balloon datasets. His graph is reproduced here as Figure 4.1.1.7.

The level of disagreement between the models and observations of tropical mid-tropospheric temperatures in Figure 4.1.1.7 is striking. It reveals, for example, the models' projected average values are 0.5°C higher than observations at the end of the record. Although these data are restricted to the tropics (from 20°N to 20°S), Spencer notes "this is where almost 50% of the solar energy absorbed by the Earth enters the climate system."

Comparing the models' output with observational data, Spencer notes the difference is "related to the lack of a middle- and upper-tropospheric 'hotspot' in the observations, which the models produce in response to surface warming combined with positive water vapor feedback," leading him to state, "the observations might be telling us that the global warming response to increasing CO_2 (and any natural warming influence) is not being amplified by water vapor."

Spencer candidly concludes:

> It is time for scientists to entertain the possibility that there is something wrong with the assumptions built into their climate models. *The fact that all of the models have been peer reviewed does not mean that any of them have been deemed to have any skill for predicting future temperatures.* In the parlance of the *Daubert* standard for rules of scientific evidence, the models have not been successfully *field tested* for predicting climate change, and so far their *error rate* should preclude their use for predicting future climate change (Harlow & Spencer, 2011) .

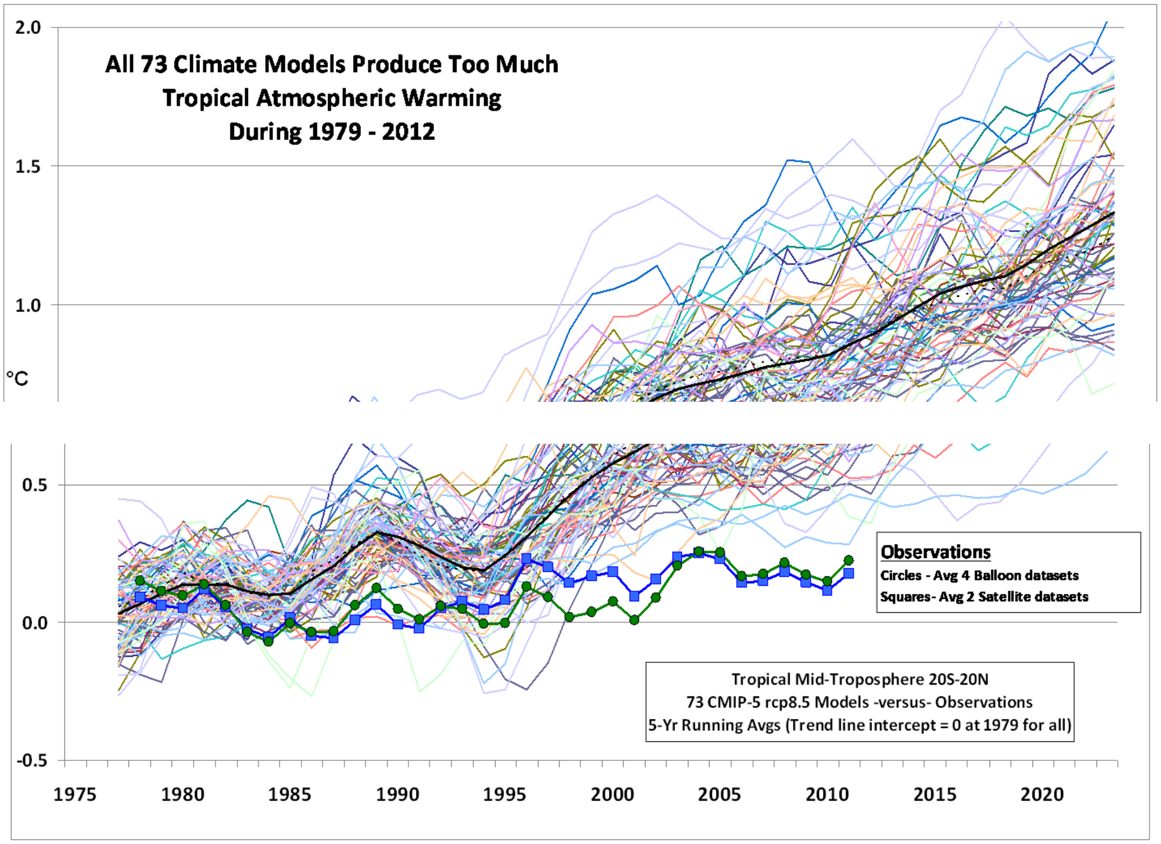

Figure 4.1.1.7. Mid-tropospheric (MT) temperature variations for the tropics (20°N to 20°S) in 73 current (CMIP5) climate models versus measurements from two satellite datasets and four weather balloon datasets. Adapted from Spencer, R.W. 2013. Statement to the U.S. Senate Environment and Public Works Committee, 19 July 2013, Washington, DC.

The fourth assumption made by the IPCC in its attribution of the late twentieth century rise in temperature to anthropogenic greenhouse gas increases is that the models correctly depict and account for natural variability. They most certainly do not, as evidenced by material presented in all of the chapters of this volume. The material presented in Section 4.2 emphasizes this point with respect to temperature, demonstrating repeatedly the reality of decadal, centennial, and millennial oscillations that occur naturally and are fully capable of explaining all of the warming experienced during the Current Warm Period. In addition, the warming of the global oceans to 2,000 m depth since the 1950s corresponds to a radiative energy imbalance of only 1 part in 1,000 (Levitus *et al*., 2012), raising the question of whether scientists can attribute this small change to humans rather than nature.

Hundreds of peer-reviewed papers have presented evidence indicating temperatures of the past several decades are not unusual, unnatural, or unprecedented on a hemispheric or global scale. It is very likely the magnitude of prior warmth, such as what was experienced during both the Roman and Medieval Warm Periods, exceeded or was at least equal to the warmth of the Current Warm Period. Since temperatures were as warm back then, when atmospheric CO_2 concentrations were much lower than they are now, there are valid empirical reasons to conclude the temperature increase of the past century has occurred independently of the concomitant 40 percent increase in atmospheric CO_2. Real-world observations reveal the Current Warm Period is simply a manifestation of the natural progression of a persistent millennial-scale climate oscillation that regularly brings Earth several-hundred-year periods of modestly higher and lower temperatures totally independent of variations in atmospheric CO_2 concentration.

Clearly, the IPCC's attribution of recent twentieth century warming to rising greenhouse gas concentrations is speculative at best.

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4.1.2 Urbanization Biases Still Taint Modern Temperature Records

The warming of near-surface air over non-urban areas of the planet during the past one to two centuries is believed to have been less than 1°C. Warming in many growing cities, on the other hand, may have been a full order of magnitude greater. Thus, since nearly all near-surface air temperature records of this period have been obtained from sensors located in population centers that have experienced significant growth, it is essential that urbanization-induced warming be removed from all original temperature records when attempting to accurately assess what has truly happened in the natural non-urban environment.

According to the IPCC, such urban influences have been mathematically accounted for and removed from the temperature records they utilize, effectively allowing them to conclude most of the remaining warming of the past few decades is the result of a human influence.

> Recent studies confirm that effects of urbanization and land use change on the global temperature

> record are negligible (less than 0.006°C per decade over land and zero over the ocean) as far as hemispheric and continental-scale averages are concerned. All observations are subject to data quality and consistency checks to correct for potential biases. The real but local effects of urban areas are accounted for in the land temperature data sets used (Technical Summary of AR4, p. 36)
>
> It is *likely* that urban heat-island effects and land use change effects have not raised the centennial global land surface air temperature trends by more than 10% of the observed trend. This is an average value; in some regions that have rapidly developed, urban heat island and land use change impacts on regional trends have been substantially larger (Second Order Draft of AR5, dated October 5, 2012, p. 2-4)

The 0.006°C per decade figure is presented as a research finding, but it is derived from mere conjecture. Section 2.3.3 of Brohan *et al*. (2006) states that to properly adjust the data would require a global comparison of urban versus rural records, but classifying records in this way is not possible since "no such complete meta-data are available" (p. 11), so the authors instead made an arbitrary assumption (p. 11) that the bias is no larger than 0.06 degrees per century.

As shown in the subsections below, filtering out urbanization and related land-use effects in the temperature record is a complicated task. There is solid evidence the methods currently used are inadequate, implying urbanization may account for a larger portion of the modern temperature rise than the IPCC acknowledges. Based on the studies reviewed below, it would appear almost certain surface-based temperature histories of the globe contain a significant warming bias introduced by insufficient corrections for the urban heat island effect. It may be impossible to make proper corrections for this deficiency, as the urban heat island effect of even small towns dwarfs any concomitant augmented greenhouse effect that may be present.

4.1.2.1 Global

Using a global dataset developed by Van Aardenne *et al*. (2001) that reveals the spatial distribution of levels of industrial activity over the planet as quantified by the intensity of anthropogenic CO_2 emissions, De Laat and Maurellis (2004) divided the surface of Earth into nonindustrial and industrial sectors of various intensity levels. They then plotted the 1979–2001 temperature trends (°C/decade) of the sectors using data from the surface and the lower and middle troposphere. The two scientists determined "measurements of surface and lower tropospheric temperature change give a very different picture from climate model predictions and show strong observational evidence the degree of industrialization is correlated with surface temperature increases as well as lower tropospheric temperature changes." They found the surface and lower tropospheric warming trends of all industrial regions were greater than the mean warming trend of Earth's nonindustrial regions, and the difference in warming rate between the two types of land-use grows ever larger as the degree of industrialization increases.

De Laat and Maurellis note, "areas with larger temperature trends (corresponding to higher CO_2 emissions) cover a considerable part of the globe," which implies "the 'real' global mean surface temperature trend is very likely to be considerably smaller than the temperature trend in the CRU [Hadley Center/Climate Research Unit] data," since the temperature measurements in that database "are often conducted in the vicinity of human (industrial) activity." These observations, they write, "suggest a hitherto-overlooked driver of local surface temperature increases, which is linked to the degree of industrialization" and lend "strong support to other indications that surface processes (possibly changes in land-use or the urban heat effect) are crucial players in observed surface temperature changes (Kalnay and Cai, 2003; Gallo *et al*., 1996, 1999)." Thus they conclude "the observed surface temperature changes might be a result of local surface heating processes and not related to radiative greenhouse gas forcing."

McKitrick and Michaels (2004) calculated 1979–2000 linear trends of monthly mean near-surface air temperature for 218 stations in 93 countries, using raw station data obtained from the Goddard Institute of Space Studies (GISS). They regressed the results against indicators of local economic activity such as income, gross domestic product growth rates, and coal use. They found, as expected, correlations between the spatial patterns of local socioeconomic measures and the magnitude of warming trends.

They repeated the process using the gridded surface air temperature data of the Climatic Research Unit (CRU) that had been adjusted to remove such effects. They found smaller but similar patterns that were statistically significant and added up to a net warming bias, although they note "precise estimation of its magnitude will require further work." Providing that estimation in a follow-up paper three years later, McKitrick and Michaels (2007) conclude the net warming bias accounted for "about half" of the estimated 1980–2002 global average temperature trend over land.

These and similar studies evidently posed a problem for the lead authors of the IPCC AR4, since their estimates of the magnitude of twentieth century warming and its attribution to GHGs relied on the assumption that the surface temperature record was more or less uncontaminated. For example, in one of the Climategate emails from IPCC Lead Author Phil Jones to his colleague Michael Mann, dated July 8, 2004, Jones confided he and IPCC coauthor Kevin Trenberth were determined to keep this evidence out of the IPCC report:

> I can't see either of these papers being in the next IPCC report. Kevin [Trenberth] and I will keep them out somehow—even if we have to redefine what the peer-review literature is!

Consistent with that plan, no mention of these studies was made in the IPCC report drafts shown to reviewers. After the close of expert review, a statement was inserted into the published version (IPCC 2007, Chapter 3, p. 244) acknowledging the spatial pattern of warming matched that of industrialization but claiming "the correlation of warming with industrial and socioeconomic development ceases to be statistically significant" once the effects of atmospheric circulation changes are taken into account, a claim for which there was no supporting evidence. McKitrick (2010) subsequently tested the claim and showed it to be untrue. The U.S. Environmental Protection Agency nevertheless relied verbatim on this claim in its dismissal of comments on an endangerment finding related to greenhouse gas emissions (see http://www.epa.gov/climatechange/endangerment/comments/volume2.html#2).

Klotzbach *et al*. (2009) tested the data contamination issue in a different way. If there is no contamination of surface data due to land use changes, they noted, the difference between surface trends and satellite-based measures of the lower troposphere should be constant over time. But the trends diverge, and the divergence runs opposite to the direction predicted by climate models. They conclude contamination of the surface data through land surface changes was a likely explanation.

Schmidt (2009) claims the McKitrick and Michaels results are likely spurious because of spatial autocorrelation in the temperature data, and he asserts it was unlikely similar patterns could be found across different climate datasets. He claims similar correlations could be found in GCM-generated data that, by construction, is not contaminated with urbanization. But Schmidt did not test his assertion about spatial autocorrelation, and his model-generated data failed to exhibit the claimed correlations.

McKitrick and Nierenberg (2010) tested Schmidt's conjectures in detail and showed them to be untrue. The evidence of data contamination was shown to be consistent across multiple combinations of surface and satellite data. It was not affected by spatial autocorrelation and it could not be replicated in data generated by the GISS climate model.

McKitrick and Tole (2012) went further and examined all 22 climate models used for the AR4, testing the models' ability to explain the spatial pattern of trends over 1979–2002, alone or in any linear combination, in comparison with indicators of urbanization and fixed geographical factors. After removing the 10 GCMs that generated predicted surface temperature trends anti-correlated with observations, they used Bayesian Model Averaging to evaluate 2^{19} possible linear combinations of explanatory models. They conclude only 2 of 22 climate models had significant explanatory power, and the optimal model of surface temperature changes required inclusion of measures of industrialization.

The IPCC also has relied on an argument by Parker (2004, 2006), who examined nighttime minimum urban temperature trends. He argues if urbanization had a significant effect, the observed warming would be less in a sample selected on nights with higher wind speed, but he found no such differences. He concludes urban warming could not be a significant factor in global averages. More recently, Wickham *et al*. (2013) tested the issue by partitioning the Berkeley Earth Surface Temperature (BEST) dataset using satellite-based measures of rural and urban locations and found no significant difference in average trends, likewise concluding land surface changes could not be a factor in global average trends.

Neither of these approaches addressed the evidence in the original McKitrick and Michaels (2004, 2007) studies. McKitrick (2013) demonstrated a Parker-type result, with equivalent trends on calm and windy nights, could be replicated on a dataset known on independent grounds to be contaminated with strong urbanization effects. And he demonstrated the Wickham *et al*. methodology was defective because their results were consistent either with the absence of an urbanization bias or its presence, and a more detailed statistical model would be required to determine which actually was the case.

That an urban heat island-induced error has indeed corrupted databases claimed to be immune from it is also suggested by the work of Hergerl and Wallace (2000), who attempted to determine whether trends in recognizable atmospheric modes of variability could account for all or part of the observed trend in surface-troposphere temperature differential; i.e., lapse rate, which has been driven by the upward-inclined trend in surface-derived temperatures and the nearly level trend in satellite-derived tropospheric temperatures over the last two decades of the twentieth century.

The two researchers found "modes of variability that affect surface temperature cannot explain trends in the observed lapse rate," and "no mechanism with clear spatial or time structure can be found that accounts for that trend." In addition, they acknowledge "all attempts to explain all or a significant part of the observed lapse rate trend by modes of climate variability with structured patterns from observations have failed," and "an approach applying model data to isolate such a pattern has also failed." Nor could they find any evidence "that interdecadal variations in radiative forcing, such as might be caused by volcanic eruptions, variations in solar output, or stratospheric ozone depletion alone, offer a compelling explanation." They conclude, "there remains a gap in our fundamental understanding of the processes that cause the lapse rate to vary on interdecadal timescales."

One reason no meteorological or climatic explanation could be found for the ever-increasing difference between the surface- and satellite-derived temperature trends of the past 20-plus years may be that one of the temperature records is incorrect. Faced with this possibility, one might want to determine which of the records is likely to be erroneous and then assess the consequences of that determination. Although this task may seem daunting, it is not that difficult. Hergerl and Wallace found good correspondence between the satellite and radiosonde temperature trends, leaving little reason to doubt the veracity of the satellite results, since this comparison essentially amounts to an *in situ* validation of the satellite record. It would be easy for a spurious warming of 0.12°C per decade to be introduced into the surface air temperature trend as a consequence of the worldwide intensification of the urban heat island effect likely driven by the worldwide population increase that manifested in most of the places where surface air temperature measurements were made over the last two decades of the twentieth century.

Other scientists have considered whether the urban heat island is affected by the direct heating of near-surface air in towns and cities by the carbon dioxide dome that occurs above them. Balling *et al*. (2002) obtained vertical profiles of atmospheric CO_2 concentration, temperature, and humidity over Phoenix, Arizona from measurements made in association with once-daily aircraft flights conducted over a 14-day period in January 2000 that extended through, and far above, the top of the city's urban CO_2 dome during the times of the latter's maximum manifestation. They employed a one-dimensional infrared radiation simulation model to determine the thermal impact of the urban CO_2 dome on the near-surface temperature of the city.

The researchers found the CO_2 concentration of the air over Phoenix dropped off rapidly with altitude, returning from a central-city surface value on the order of 600 ppm to a normal non-urban background value of approximately 378 ppm at an air pressure of 800 hPa, creating a calculated surface warming of only 0.12°C at the time of maximum CO_2-induced warming potential, about an order of magnitude less than the urban heat island effect of cities the size of Phoenix. The authors conclude the warming induced by the urban CO_2 dome of Phoenix is possibly two orders of magnitude smaller than what is produced by other sources of the city's urban heat island. Although human activities are indeed responsible for high urban air temperatures, which can rise 10°C or more above those of surrounding rural areas, these high values are not the result of a local CO_2-enhanced greenhouse effect.

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4.1.2.2 Asia

In a study of the urban heat island effect in South Korea, Choi *et al*. (2003) compare the mean station temperatures of three groupings of cities (one comprised of four large urban stations with a mean 1995 population of 4,830,000, one of six smaller urban stations with a mean 1995 population of 548,000, and one of six "rural" stations with a mean 1995 population of 214,000) over the period 1968–1999. They found the "temperatures of large urban stations exhibit higher urban bias than those of smaller urban stations and that the magnitude of urban bias has increased since the late 1980s." They note "estimates of the annual mean magnitude of urban bias range from 0.35°C for smaller urban stations to 0.50°C for large urban stations," concluding "none of the rural stations used for this study can represent a true non-urbanized environment." They say their results are underestimates of the true urban effect, and "urban growth biases are very serious in South Korea and must be taken into account when assessing the reliability of temperature trends."

In a second study conducted in South Korea, Chung *et al*. (2004a) report there was an "overlapping of the rapid urbanization-industrialization period with the global warming era," and the background climatic trends from urbanized areas might therefore be contaminated by a growing urban heat island effect. To investigate this possibility, "monthly averages of daily minimum, maximum, and mean temperature at 14 synoptic stations were prepared for 1951–1980 (past normal) and 1971–2000 (current normal) periods," and "regression equations were used to determine potential effects of urbanization and to extract the net contribution of regional climate change to the apparent temperature change." Twelve of these stations were growing urban sites of various size, and two (where populations actually decreased) were rural, one being located inland and one on a remote island.

Over the 20 years that separated the two normal periods, Chung *et al*. report that in Seoul, where population increase was greatest, annual mean daily minimum temperature increased by 0.7°C, while a 0.1°C increase was detected at one of the two rural sites and a 0.1°C decrease was detected at the other, for no net change in their aggregate mean value. In the case of annual mean daily maximum temperature, a 0.4°C increase was observed at Seoul and a 0.3°C increase was observed at the two rural sites. Thus the change in the annual mean daily mean temperature was an increase of 0.15°C at the two rural sites, indicative of regional background warming of 0.075°C per decade. The change of annual mean daily mean temperature at Seoul was an increase of 0.55°C, or 0.275°C per decade, indicative of an urban-induced warming of 0.2°C per decade in addition to the regional background warming of 0.075°C per decade. Corresponding results for urban areas of intermediate size defined a linear relationship that connected these two extreme results when plotted against the logarithm of population increase over the two-decade period.

In light of the significantly intensifying urban heat island effect detected in their study, Chung *et al*. say it is "necessary to subtract the computed urbanization effect from the observed data at urban stations in order to prepare an intended nationwide climatic atlas," noting "rural climatological normals should be used instead of the conventional normals to simulate ecosystem responses to climatic change, because the urban area is still much smaller than natural and agricultural ecosystems in Korea."

Chung *et al*. (2004b) evaluated temperature changes at ten urban and rural Korean stations over the period 1974–2002. They found "the annual temperature increase in large urban areas was higher than that observed at rural and marine stations." Specifically, they note, "during the last 29 years, the increase in annual mean temperature was 1.5°C for Seoul and 0.6°C for the rural and seashore stations," while increases in mean January temperatures ranged from 0.8 to 2.4°C for the ten stations. In addition, they state, "rapid industrialization of the Korean Peninsula occurred during the late 1970s and late 1980s," and when plotted on a map, "the remarkable industrialization and expansion ... correlate[s] with the distribution of increases in temperature." Consequently, Chung *et al*. (2004b) found much, and in many cases most, of the warming experienced over the past several decades in the urban areas of Korea was the result of local urban influences not indicative of regional background warming.

Kim and Kim (2011) derived values of the total warming for cities on the Korean peninsula with temperature data from four cities covering the period 1909–2008, 12 cities covering 1954–2008, and 20 cities covering 1969–2008. Values of the urban warming effect were derived "by using the warming mode of Empirical Orthogonal Function (EOF) analysis of the 55 years of temperature data from 1954 to 2008." The estimated amounts of urban warming were verified by means of a multiple linear regression equation with two independent variables: rate of population growth and total population. By subtracting the temperature increase due to urbanization from the total temperature increase of each city, they obtained what they call "greenhouse warming," although it should more appropriately be identified as background warming, natural warming, or non-urban-induced warming, because forcings other than greenhouse gases may play a major role in the non-urban-induced portion of the total observed warming.

Kim and Kim report the mean total warming of the 12 cities over the period 1954–2008 was 1.37°C, of which 0.77°C was due to the growth of their urban heat islands and the remaining 0.60°C was due to other factors. In addition, they found "urban warming depends more on the population percent growth rate than the average population." In the case of Pohang and Incheon, for example, which "have rapidly increasing populations due to rapid industrialization," they note "the degree of urbanization was great." In the case of Busan, which has a large and steady population, they discovered "the degree of urbanization was weak." Thus "the rising trend of temperature appeared stronger in newly industrialized cities more than in large cities."

Weng (2001) evaluated the effect of land cover changes on surface temperatures of the Zhujiang Delta (an area of slightly more than 17,000 km^2) via a series of analyses of remotely sensed Landsat Thematic Mapper data. They found between 1989 and 1997 the area of land devoted to agriculture declined by nearly 50 percent, while urban land area increased by close to the same percentage. After normalizing the surface radiant temperature for the years 1989 and 1997, they used image differencing to produce a radiant temperature change image, which they overlaid with images of urban expansion. The results indicated "urban development between 1989 and 1997 has given rise to an average increase of 13.01°C in surface radiant temperature."

Chen *et al*. (2003) evaluated several characteristics of Shanghai's urban heat island, including its likely cause, based on analyses of monthly meteorological data from 1961 to 1997 at 16 stations in and around this hub of economic activity that is one of the most flourishing urban areas in all of China. Defining the urban heat island of Shanghai as the mean annual air temperature difference between urban Longhua and suburban Songjiang, Chen *et al*. found its strength increased in essentially linear fashion from 1977 to 1997 by 1°C.

Chen *et al*. conclude "the main factor causing the intensity of the heat island in Shanghai is associated with the increasing energy consumption due to economic development," noting in 1995 the Environment Research Center of Peking University determined the annual heating intensity due to energy consumption by human activities was approximately 25 Wm^{-2} in the urban area of Shanghai but only 0.5 Wm^{-2} in its suburbs. In addition, they point out the 0.5°C/decade intensification of Shanghai's urban heat island is an order of magnitude greater than the 0.05°C/decade global warming of Earth over the past century, suggesting the ongoing intensification of even already-strong urban heat islands cannot be discounted.

Kalnay and Cai (2003) used differences between trends in directly observed surface air temperature and trends determined from the NCEP-NCAR 50-year Reanalysis (NNR) project (based on atmospheric vertical soundings derived from satellites and balloons) to estimate the impact of land-use changes on surface warming. Over undisturbed rural areas of the United States, they found the surface- and reanalysis-derived air temperature data yielded essentially identical trends, implying differences between the two approaches over urban areas would represent urban heat island effects. Zhou *et al*. (2004) applied the same technique over southeast China, using an improved version of reanalysis that includes newer physics, observed soil moisture forcing, and a more accurate characterization of clouds.

For the period January 1979 to December 1998, the eight scientists derived an "estimated warming of mean surface [air] temperature of 0.05°C per decade attributable to urbanization," which they say "is much larger than previous estimates for other periods and locations, including the estimate of 0.027°C for the continental U.S. (Kalnay and Cai, 2003)." They note, however, because their analysis "is from the winter season over a period of rapid urbanization and for a country with a much higher population density, we expect our results to give higher values than those estimated in other locations and over longer periods."

Zhang *et al*. (2005) used the approach of Kalnay and Cai (2003) to determine the impacts of land-use changes on surface air temperature throughout eastern China (east of 110°E), where rapid urbanization, deforestation, desertification, and other changes in land use have occurred over the past quarter-century, focusing on daily mean, maximum, and minimum air temperatures from 259 stations over the period 1960–1999. Their analyses indicate changes in land use had little or no influence on daily maximum temperatures, but they explain about 18 percent of the observed daily mean temperature increase and 29 percent of the observed daily minimum temperature increase in this region over the past 40 years, yielding decadal warming trends of about 0.12°C and 0.20°C for these two parameters, respectively.

Frauenfeld *et al*. (2005) used daily surface air temperature measurements from 161 stations located throughout the Tibetan Plateau (TP) to calculate the region's mean annual temperature for each year from 1958 through 2000, plus 2-meter temperatures from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40), which "are derived from rawinsonde profiles, satellite retrievals, aircraft reports, and other sources including some surface observations." This approach, they write, results in "more temporally homogeneous fields" that provide "a better assessment of large-scale temperature variability across the plateau." Over the period 1958–2000, Frauenfeld *et al*. report, "time series based on aggregating all station data on the TP show a statistically significant positive trend of 0.16°C per decade," as also has been reported by Liu and Chen (2000). However, they state, "no trends are evident in the ERA-40 data for the plateau as a whole."

In discussing this discrepancy, the three scientists suggest "a potential explanation for the difference between reanalysis and station trends is the extensive local and regional land use change that has occurred across the TP over the last 50 years." They note, for example, "over the last 30 years, livestock numbers across the TP have increased more than 200% due to inappropriate land management practices and are now at levels that far exceed the carrying capacity of the region (Du *et al*., 2004)." The resultant overgrazing, they write, "has caused land degradation and desertification at an alarming rate (Zhu and Li, 2000; Zeng *et al*., 2003)," and "in other parts of the world, land degradation due to overgrazing has been shown to cause significant local temperature increases (e.g., Balling *et al*., 1998)."

They also note "urbanization, which can result in 8°–11°C higher temperatures than in surrounding rural areas (e.g., Brandsma *et al*., 2003), has also occurred extensively on the TP," as "construction of a gas pipeline in the 1970s and highway expansion projects in the early 1980s have resulted in a dramatic population influx from other parts of China, contributing to both urbanization and a changed landscape." Thus they state, "the original Tibetan section of Lhasa (i.e., the pre-1950 Lhasa) now only comprises 4% of the city, suggesting a 2400% increase in size over the last 50 years." And they note "similar population increases have occurred at other locations across the TP," and "even villages and small towns can exhibit a strong urban heat island effect."

Frauenfeld *et al*. contend "these local changes are reflected in station temperature records." We agree, and we note when the surface-generated anomalies are removed, as in the case of the ERA-40 reanalysis results they present, it is clear there has been no warming of the Tibetan Plateau since at least 1958. Other results reported in this section imply much the same about other parts of China and greater Asia. Thus the dramatic surface-generated late twentieth century warming of the world claimed by the IPCC, Mann *et al*. (1998, 1999), and Mann and Jones (2003) to represent mean global background conditions likely significantly overestimates the warming over the past 30 years and is therefore not a true representation of Earth's recent temperature history.

Based on temperature data obtained at the "national reference and basic stations" at Beijing and Wuhan, China, plus similar data from six rural stations near Beijing and four rural stations near Wuhan, Ren *et al*. (2007) calculated the rates of temperature rise over the periods 1961–2000 and 1981–2000 to determine what portion of the observed warming at these stations is truly background warming and what is spurious, urban-induced warming.

The authors determined the rate of increase in annual mean surface air temperature over the period 1961–2000 was 0.32°C/decade and 0.31°C/decade, respectively, for Beijing and Wuhan, but only 0.06°C/decade and 0.11°C/decade for the corresponding sets of rural stations that surround them. Spurious urban warming was responsible for more than 80 percent of the 1961–2000 temperature increase at Beijing and a little more than 64 percent of the temperature increase at Wuhan. For the period 1981–2000, spurious urban warming accounted for 61 percent of the Beijing temperature increase and 40 percent of the Wuhan increase. The researchers also report the Beijing and Wuhan stations are not located in the central parts of the cities, and their findings are thus not representative of the cities' downtown areas, where urban heat island effects would be expected to be even greater.

Ren *et al*. note the impact of urbanization on the surface air temperature trends of the two mega-city stations is much larger than what is reported for North China as a whole and for Hubei Province. Consequently, they conclude "it is likely that a larger part of the surface air temperature increase in the country as obtained from … national reference and basic stations has been caused by [an] enhanced urban heat island effect during the past decades." They say there is "a need for paying more attention to the selection of observational sites, and for further detecting and adjusting the urbanization-induced bias probably existing in surface air temperature records of city stations."

Ren *et al*. (2008) employed a dataset obtained from 282 meteorological stations, including all of the ordinary and national basic and reference weather stations of north China, to determine the urbanization effect on surface air temperature trends of that part of the country over the period 1961–2000. They categorized the stations based on city size expressed in millions of people: rural (<0.05), small city (0.01–0.10), medium city (0.10–0.50), large city (0.50–1.00), and metropolis (>1.00). They found mean annual surface air temperature trends over the period, in degrees C per decade, were 0.18 (rural), 0.25 (small city), 0.28 (medium city), 0.34 (large city), 0.26 (metropolis), and 0.29 (national), making the urban-induced component of the warming trend 0.07 (small city), 0.10 (medium city), 0.16 (large city), 0.08 (metropolis), and 0.11 (national), all of which are significant at the 0.01 level. The seven Chinese researchers conclude it is "obvious that, in the current regional average surface temperature series in north China, or probably in the country as a whole, there still remain large effects from urban warming," noting "the contribution of urban warming to total annual mean surface air temperature change as estimated with the national basic/reference dataset reaches 37.9%."

Yang *et al*. (2011) note the IPCC's *Fourth Assessment Report* states urban heat island (UHI) effects are real but only "local and have a negligible influence on global warming trends." However, Yang *et al.* write, the UHI effect is regarded by others "as one of the major errors or sources of uncertainty in current surface warming studies," citing Gong and Wang (2002) and Heisler and Brazel (2010). They state, "some research results indicate that this effect may play a more significant role in temperature trends estimated at multiple geographic scales," noting Pielke (2005) and Stone (2009) suggest "such results should be accorded more consideration in the mitigation of climate change."

Yang *et al*. use monthly mean surface air temperature data from 463 meteorological stations, including those from the 1981–2007 ordinary and national basic reference surface stations in east China and from the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) Reanalysis, to investigate the effect of rapid urbanization on temperature change for six different categories of population size or density—metropolis, large city, medium-sized city, small city, suburban, and rural—as determined from satellite-measured nighttime light imagery and census data. The three researchers state their findings indicate "rapid urbanization has a significant influence on surface warming over east China," noting, "overall, UHI effects contribute 24.2% to regional average warming trends" and "the strongest effect of urbanization on annual mean surface air temperature trends occurs over the metropolis and large city stations, with corresponding contributions of about 44% and 35% to total warming, respectively," with UHI trends of 0.398°C and 0.26°C per decade. They also say the UHI warming trends and their contributions to the overall warming over east China provided in their paper "can still be regarded as conservative."

If such UHI trends continue, the Chinese scientists conclude, "certain metropolitan areas may experience a rate of warming well beyond the range projected by the global climate change scenarios of the IPCC," referencing Stone (2007), while adding, "the increasing divergence between urban and rural surface temperature trends highlights the limitations of the response policy to climate change [that] focus only on greenhouse gas reduction," citing Stone (2009).

Zhou and Ren (2011) used the daily temperature records of 526 measurement stations included among the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration to evaluate trends in 15 extreme temperature indices for the period 1961–2008. Based on the earlier findings of Zhou and Ren (2009), which indicated the contribution of urban warming to overall warming often exceeded 50 percent, they adjusted their results to account for the impact of each site's urban heat island effect.

They discovered "urbanization intensified the downward trend in cold index series and the upward trend in warm indices related to minimum temperature." They report "the urbanization effect on the series of extreme temperature indices was statistically significant for the downward trends in frost days, daily temperature range, cool nights, and cool days," as well as for "the upward trends in summer days, tropical nights, daily maximum temperature, daily minimum temperature, and warm nights." For these indices, they state, "the contributions of the urbanization effect to the overall trends ranged from 10 to 100%, with the largest contributions coming from tropical nights, daily temperature range, daily maximum temperature and daily minimum temperature," adding, "the decrease in daily temperature range at the national stations in North China was caused entirely by urbanization."

Regarding the urban heat island phenomenon, the two researchers conclude their paper by stating "more attention needs to be given to the issue in future studies."

Gao and Liu (2012) studied the effect of the deforestation of portions of Heilongjiang Province in Northeast China, which has an annual temperature ranging from -4°C to +4°C, with its winters being "long and frigid" and its summers "short and cool." Their study covered two periods: 1958–1980, when forest cover was reduced from 238,335 km^2 to 216,009 km^2; and 1980–2000, when forest cover was further reduced to 207,629 km^2. Over the entire period the two researchers analyzed (1958–2000), there was a nationwide warming of 0.99°C, whereas the annual temperature of Heilongjiang Province rose by 1.68°C, which suggests a concomitant deforestation-induced warming of 0.69°C. Thus, in response to the 13 percent reduction in forest cover over the 42-year interval Gao and Liu analyzed, the mean annual temperature of Heilongjiang Province rose by 0.69°C, a substantial amount considering the temperature of the globe had risen by an average of only about 0.7°C since the start of the Industrial Revolution.

Tokairin *et al*. (2010) note the population of Jakarta, the capital of Indonesia, was approximately 12 million in 2000, whereas it had been about 5 million in the 1970s. They note the rapid population increase of the past few decades brought a rapid expansion of the city's urban area, adding to the strength of the urban heat island of the original "old city" of the 1970s. To evaluate the warming power of the newer infrastructure added around the central old city, Tokairin *et al*. analyzed the air temperature increase in the initially urbanized area of Jakarta over the 30-year period between the 1970s and the 2000s, using air temperature data provided by the country's National Climatic Data Center. They made a rough estimate of the sensible heat in the old city during the 2000s that originated in, and was transported from, the newly developed urban area.

The three researchers report "the sea breeze developed at an earlier time of day in the present day than in the 1970s" and "in the present-day case, a converging flow developed over the old city in association with the low pressure which formed over the same location." They further note "the daytime average and maximum air temperature in the old city were higher in the present day than in the 1970s by 0.6 and 0.9°C , respectively, due to the advection of heat from the new area" and "the amount of heat advected into the old city was estimated to be -0.7 Wm^{-2} in the 1970s and 77 Wm^{-2} in the 2000s."

Fujibe (2011) writes, "in the context of global climate change, urban warming can bias results obtained for background monitoring, as many of the observatories that have been in operation for a long time are located in cities." Nevertheless, Fujibe notes, the IPCC (2007) has suggested "the globally averaged temperature trend is hardly affected by urbanization." Unconvinced of the validity of the IPCC's assertion, the Japanese researcher reviews what is known about the subject based on research conducted in Japan.

Fujibe reports "the recorded rate of temperature increase is a few degrees per century in large cities and tends to be larger at night than during the daytime." In some cities, "the increase in annual extreme minimum temperature exceeds 10°C per century." Fujibe notes numerous studies have detected heat islands in small settlements "with a population of 1000 or less," as reported by Tamiya (1968), Tamiya and Ohyama (1981), Sakakibara and Morita (2002), Sakakibara and Kitahara (2003), and Sakakibara and Matsui (2005), where statistically significant trends on the order of 0.04°C per decade have been observed. Fujibe concludes, "urban warming can be a biasing factor that may contaminate data used for monitoring the background temperature change," with locations with low population densities of 100–300 people per square kilometer "showing a statistically significant anomalous trend of 0.04°C per decade."

Clearly, a substantial part of the past half-century's global warming, which the IPCC attributes to the greenhouse effect of CO_2 and methane, is nothing more than a manifestation of the well-known urban heat island effect, which is not properly removed from the various databases discussed here and probably many others. If such spurious warming is not accounted and appropriately adjusted for, public and scientific confidence in the quality of global temperature datasets will continue to decline.

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4.1.2.3 North America

In studying the urban heat island (UHI) of Houston, Texas, Streutker (2003) analyzed 82 sets of nighttime radiation data obtained from the split-window infrared channels of the Advanced Very High Resolution Radiometer on board the NOAA-9 satellite during March 1985 through February 1987 and from 125 sets of similar data obtained from the NOAA-14 satellite during July 1999 through June 2001. Between these two periods, the mean nighttime surface temperature of Houston rose by 0.82 ± 0.10 °C. In addition, Streutker notes the growth of the Houston UHI, both in magnitude and spatial extent, "scales roughly with the increase in population," and the mean rural temperature measured during the second interval was "virtually identical to the earlier interval."

Streutker's work demonstrates the UHI phenomenon can be very powerful, for in just 12 years the UHI of Houston grew by more than the IPCC contends the mean surface air temperature of the planet rose over the entire past century, when Earth's population rose by approximately 280 percent, or nearly an order of magnitude more than the 30 percent population growth experienced by Houston over the 12 years of Streutker's study.

Maul and Davis (2001) analyzed air and seawater temperature data obtained over the past century at the sites of several primary tide gauges maintained by the U.S. Coast and Geodetic Survey. Noting each of these sites "experienced significant population growth in the last 100 years," and "with the increase in maritime traffic and discharge of wastewater one would expect water temperatures to rise" (due to a maritime analogue of the urban heat island effect), they calculated trends for the 14 longest records and derived a mean century-long seawater warming of 0.74°C, with Boston registering an anomalous 100-year warming of 3.6°C. In addition, they report air temperature trends at the tide gauge sites, which represent the standard urban heat island effect, were "much larger" than the seawater temperature trends.

Dow and DeWalle (2000) analyzed trends in annual evaporation and Bowen ratio measurements on 51 eastern U.S. watersheds that experienced various degrees of urbanization between 1920 and 1990. They determined as residential development progressively occurred on what originally were rural watersheds, watershed evaporation decreased and sensible heating of the atmosphere increased. And from relationships derived from the suite of watersheds investigated, they calculated complete transformation from 100 percent rural to 100 percent urban characteristics resulted in a 31 percent decrease in watershed evaporation and a 13 Wm^{-2} increase in sensible heating of the atmosphere.

Climate modeling exercises suggest a doubling of the air's CO_2 concentration will result in a nominal 4 Wm^{-2} increase in the radiative forcing of Earth's surface-troposphere system, which often has been predicted to produce an approximate 4°C increase in the mean near-surface air temperature of the globe, indicative of an order-of-magnitude climate sensitivity of 1°C per Wm^{-2} change in radiative forcing. Thus, to a first approximation, the 13 Wm^{-2} increase in the sensible heating of the near-surface atmosphere produced by the total urbanization of a pristine rural watershed in the eastern United States reported by Dow and DeWalle could be expected to produce an increase of about 13°C in near-surface air temperature over the central portion of the watershed, which is consistent with maximum urban heat island effects observed in large and densely populated cities. Therefore, a 10 percent rural-to-urban transformation could produce a warming on the order of 1.3°C, and a mere 2 percent transformation could increase the near-surface air temperature by as much as a quarter of a degree Centigrade.

This powerful anthropogenic but non-greenhouse-gas-induced effect of urbanization on the energy balance of watersheds and the temperature of the boundary-layer air above them begins to express itself with the very first hint of urbanization and, hence, may be readily overlooked in studies seeking to identify a greenhouse-gas-induced global warming signal. In fact, the fledgling urban heat island effect already may be present in many temperature records routinely been considered "rural enough" to be devoid of all human influence, when in fact that may be far from the truth.

A case in point is provided by the study of Changnon (1999), who used a series of measurements of soil temperatures obtained in a completely rural setting in central Illinois between 1889 and 1952 and a contemporary set of air temperature measurements made in an adjacent growing community (plus similar data obtained from other nearby small towns) to evaluate the magnitude of unsuspected heat island effects that might be present in small towns and cities typically assumed to be free of urban-induced warming. This work revealed soil temperature in the completely rural setting increased by 0.4°C between the decade of 1901–1910 and 1941–1950.

This warming is 0.2°C less than the 0.6°C warming determined for the same time period from the entire dataset of the U.S. Historical Climatology Network, which is supposedly corrected for urban heating effects. It is also 0.2°C less than the 0.6°C warming determined for this time period by 11 benchmark stations in Illinois with the highest-quality long-term temperature data, all of which are located in communities with populations of less than 6,000 people as of 1990. And it is 0.17°C less than the 0.57°C warming derived from data obtained at the three benchmark stations closest to the site of the soil temperature measurements and with populations of less than 2,000 people.

Changnon states his findings suggest "both sets of surface air temperature data for Illinois believed to have the best data quality with little or no urban effects may contain urban influences causing increases of 0.2°C from 1901 to 1950." He further notes "this could be significant because the IPCC (1995) indicated that the global mean temperature increased 0.3°C from 1890 to 1950."

Clearly, the efforts of this world-renowned climate specialist call all near-surface global air temperature histories into question. Until the influence of very-small-town urban heat island effects is identified and accounted for, the so-called "unprecedented" global warming of the past century, and especially the past quarter-century, cannot be accepted at face value.

DeGaetano and Allen (2002b) used data from the U.S. Historical Climatology Network to calculate trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th percentile across the United States over the period 1960–1996. In the case of daily warm minimum temperatures, the slope of the regression line fit to the data of a plot of the annual number of 95th percentile exceedences vs. year was found to be 0.09 exceedences per year for rural stations, 0.16 for suburban stations, and 0.26 for urban stations, making the rate of increase in extreme warm minimum temperatures at urban stations nearly three times greater than the rate of increase at rural stations less affected by growing urban heat islands. The rate of increase in the annual number of daily maximum temperature 95th percentile exceedences per year over the same time period was found to be 50 percent greater at urban stations than at rural stations.

Balling and Idso (2002) analyzed and compared temperature trends for the period 1979–2000 in the conterminous United States using six temperature databases:

- the unadjusted temperature data of the United States Historical Climatology Network (RAW);
- the RAW data adjusted for (a) time of observation biasing, (b) changes to the new maximum/ minimum temperature system equipment, (c) station history, including other instrument adjustments, and (d) an interpolation scheme for estimating missing data from nearby highly correlated station records (FILNET);
- essentially the FILNET data adjusted for urbanization effects (URB-ADJ);
- the updated dataset developed by Jones (1994) of the University of East Anglia (IPCC);
- the satellite-based lower-tropospheric temperature dataset (MSU2LT); and
- the radiosonde (balloon-based) temperature data that comprised "the surface reading taken the moment the balloon is launched," which "typically occurs near 1.5 m above the surface, which is near the shelter heights used in the USHCN data set" (SONDE).

In comparing the difference between the FILNET and RAW temperature trends, Balling and Idso found a nearly monotonic increase of more than 0.05°C per decade, which they found to be highly significant at the 0.0001 level of confidence. In addition, they found "the trends in the unadjusted temperature records [were] not different from the trends of the independent satellite-based lower-tropospheric temperature record or from the trend of the balloon-based near-surface measurements." The two Arizona State University Office of Climatology researchers state the adjustments made to the raw USHCN temperature data were "producing a statistically significant, but spurious, warming trend" that "approximates the widely-publicized 0.50°C increase in global temperatures over the past century."

Hinkel *et al*. (2003) installed 54 temperature-recording instruments on the Arctic Coastal Plain near the Chuckchi Sea at Barrow, Alaska in mid-June of 2001, half within the urban area and the other half distributed across approximately 150 km^2 of surrounding land, all of which provided air temperature data at hourly intervals approximately two meters above the surface of the ground. They describe the area as "the northernmost settlement in the USA and the largest native community in the Arctic," the population of which "has grown from about 300 residents in 1900 to more than 4600 in 2000."

Based on urban-rural spatial averages for the entire winter period (December 2001–March 2002), the four researchers determined the urban area to be 2.2°C warmer than the rural area. During this period, the mean daily urban-rural temperature difference increased with decreasing temperature, "reaching a peak value of around 6°C in January–February." They also determined the daily urban-rural temperature difference increased with decreasing wind speed, such that under calm conditions (< 2 m s^{-1}) the daily urban-rural temperature difference was 3.2°C in the winter. Finally, under simultaneous calm and cold conditions, the urban-rural temperature difference was observed to achieve hourly magnitudes exceeding 9°C.

For the period December 1 to March 31 of four consecutive winters, Hinkel and Nelson (2007) report the spatially averaged temperature of the urban area of Barrow was about 2°C warmer than that of the rural area, and it was not uncommon for the daily magnitude of the urban heat island to exceed 4°C. On some days, they note, the magnitude of the urban heat island exceeded 6°C, and values in excess of 8°C were sometimes recorded. The warmest individual site temperatures were "consistently observed in the urban core area," they report.

These findings indicate just how difficult it is to measure a background global temperature increase believed to have been less than 1°C over the past century (representing a warming of less than 0.1°C per decade), when the presence of a mere 4,500 people can create a winter heat island two orders of magnitude greater than the signal being sought. Temperature measurements made within the range of influence of even a small village cannot be adjusted to the degree of accuracy required to reveal the true magnitude of the pristine rural temperature change.

Ziska *et al*. (2004) characterized the gradual changes that occur in a number of environmental variables as one moves from a rural location (a farm approximately 50 km from the city center of Baltimore, Maryland) to a suburban location (a park approximately 10 km from the city center) to an urban location (the Baltimore Science Center, approximately 0.5 km from the city center). At each of these locations, four 2 x 2 m plots were excavated to a depth of about 1.1 m, after which they were filled with identical soils, the top layers of which contained seeds of naturally occurring plants of the area. These seeds sprouted in the spring of the year, and the plants they produced were allowed to grow until they senesced in the fall, after which all were cut at ground level, removed, dried, and weighed.

Along the rural-to-suburban-to-urban transect, the only consistent differences in the environmental variables they measured were a rural-to-urban increase of 21 percent in average daytime atmospheric CO_2 concentration and increases of 1.6 and 3.3°C in maximum (daytime) and minimum (nighttime) daily temperatures, respectively. These changes, they write, are "consistent with most short-term (~50 year) global change scenarios regarding CO_2 concentration and air temperature." They state, "productivity, determined as final above-ground biomass, and maximum plant height were positively affected by daytime and soil temperatures as well as enhanced CO_2, increasing 60 and 115% for the suburban and urban sites, respectively, relative to the rural site."

George *et al*. (2007) reported on five years of work at the same three transect locations near Baltimore, stating, "atmospheric CO_2 was consistently and significantly increased on average by 66 ppm from the rural to the urban site over the five years of the study," and "air temperature was also consistently and significantly higher at the urban site (14.8°C) compared to the suburban (13.6°C) and rural (12.7°C) sites." They note the increases in atmospheric CO_2 and air temperature they observed "are similar to changes predicted in the short term with global climate change, therefore providing an environment suitable for studying future effects of climate change on terrestrial ecosystems," specifically pointing out, "urban areas are currently experiencing elevated atmospheric CO_2 and temperature levels that can significantly affect plant growth compared to rural areas."

LaDochy *et al*. (2007) report, "when speculating on how global warming would impact the state [of California], climate change models and assessments often assume that the influence would be uniform (Hansen *et al*., 1998; Hayhoe *et al*., 2004; Leung *et al*., 2004)." To assess the validity of this assumption, they calculated temperature trends over the 50-year period 1950–2000 to explore the extent of warming in various subregions of the state. They then evaluated the influence of human-induced changes to the landscape on the observed temperature trends and determined their significance compared to those caused by changes in atmospheric composition, such as the air's CO_2 concentration.

The three researchers found "most regions showed a stronger increase in minimum temperatures than with mean and maximum temperatures," and "areas of intensive urbanization showed the largest positive trends, while rural, non-agricultural regions showed the least warming." They report the Northeast Interior Basins of the state experienced cooling. Large urban sites, by contrast, exhibited rates of warming "over twice those for the state, for the mean maximum temperature, and over five times the state's mean rate for the minimum temperature." They conclude, "if we assume that global warming affects all regions of the state, then the small increases seen in rural stations can be an estimate of this general warming pattern over land," which implies "larger increases," such as those they observed in areas of intensive urbanization, "must then be due to local or regional surface changes."

Rosenzweig *et al*. (2009) compared "the possible effectiveness of heat island mitigation strategies to increase urban vegetation, such as planting trees or incorporating vegetation into rooftops, with strategies to increase the albedo of impervious surfaces." They report, "surface air temperatures elevated by at least 1°C have been observed in New York City for more than a century (Rosenthal *et al*., 2003; Gaffin *et al*., 2008), and the heat island signal, measured as the difference between the urban core and the surrounding rural surface air temperature readings taken at National Weather Service stations, averages ~4°C on summer nights (Kirkpatrick and Shulman, 1987; Gedzelman *et al*., 2003; Gaffin *et al*., 2008)." The greatest temperature differences typically were sustained "between midnight and 0500 Eastern Standard Time (EST; Gaffin *et al*., 2008)." On a day they studied quite intensively (14 August 2002), they report at 0600 EST, "the city was several degrees warmer than the suburbs, and up to 8°C warmer than rural areas within 100 km of the city."

With respect to mitigation strategies, the 12 researchers determined "the most effective way to reduce urban air temperature is to maximize the amount of vegetation in the city with a combination of tree planting and green roofs." Based on modeling studies of these approaches, they estimate this strategy could reduce simulated citywide urban air temperature by 0.4°C on average and 0.7°C at 1500 EST, and reductions of up to 1.1°C at 1500 EST could be expected in some Manhattan and Brooklyn neighborhoods, "primarily because there is more available area in which to plant trees and install vegetated roofs." These findings reveal New York City already has experienced an urban-induced warming equivalent to what is predicted to occur by the end of the current century as a result of business-as-usual greenhouse gas emissions; planting additional vegetation throughout the city would likely moderate its thermal environment more than all the greenhouse-gas emissions reductions the world's governments are ever likely to make.

Imhoff *et al*. (2010) note the urban heat island (UHI) phenomenon is "caused by a reduction in latent heat flux and an increase in sensible heat in urban areas as vegetated and evaporating soil surfaces are replaced by relatively impervious low-albedo paving and building materials," and this replacement "creates a difference in temperature between urban and surrounding non-urban areas." Most studies of this phenomenon have evaluated its magnitude by means of ground-based measurements of near-surface air temperature made at urban and rural weather stations, and they have found the urban-rural air temperature difference is expressed most strongly at night. Imhoff *et al*., however, employed satellite-based measurements of surface temperature, and they found this alternative measure of the UHI was most strongly expressed during the day.

The authors' analysis included 38 of the most populous cities in the continental United States and their rural surroundings, where Imhoff *et al*. obtained land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on NASA's Earth Observing System (EOS) satellites, which they used in a spatial analysis to assess UHI skin temperature amplitude and its relationship to development intensity, size, and ecological setting over three annual cycles (2003–2005), where urban impervious surface area (ISA) was obtained from the Landsat TM-based NLCD 2001 dataset.

The researchers report a city's fractional ISA was a good linear predictor of LST for all cities in the continental United States in all biomes except deserts and xeric shrublands, and the fraction of ISA explains about 70 percent of the total variance in LST for all cities combined, with the highest correlations (90 percent) in the northeastern United States, where urban areas are often embedded in temperate broadleaf and mixed forests. They also determined the largest urban-rural LST differences for all biomes occurred during the summer around midday, and the greatest amplitudes were found for urban areas that displaced forests (6.5–9.0°C) followed by temperate grasslands (6.3°C) and tropical grasslands and savannas (5.0°C). Finally, they determined the contrast between urban cores and rural zones was typically "accentuated during the time when the vegetation is physiologically active, especially in forested lands," and "the amplitude of the UHI is significantly diminished during the winter season when vegetation loses its leaves or is stressed by lower temperatures." Imhoff *et al*. conclude "the use of ISA as an estimator of the extent and intensity of urbanization is more objective than population density based methods and can be consistently applied across large areas for inter-comparison of impacts on biophysical processes."

Gonzalez *et al*. (2005) note "breezy cities on small tropical islands ... may not be exempt from the same local climate change effects and urban heat island effects seen in large continental cities," describing research they conducted in and around San Juan, Puerto Rico. A NASA Learjet carrying the Airborne Thermal and Land Applications Sensor (ATLAS) that operates in visual and infrared wavebands flew several flight lines, both day and night, over the San Juan metropolitan area, the El Yunque National Forest east of San Juan, and other nearby areas, obtaining surface temperatures, while strategically placed ground instruments recorded local air temperatures. They found surface temperature differences between urbanized areas and limited vegetated areas were higher than 30°C during daytime, creating an urban heat island with "the peak of the high temperature dome exactly over the commercial area of downtown," where noontime air temperatures were as much a 3°C greater than those of surrounding rural areas. In addition, the 11 researchers report, "a recent climatological analysis of the surface [air] temperature of the city has revealed that the local temperature has been increasing over the neighboring vegetated areas at a rate of 0.06°C per year for the past 30 years."

Gonzalez *et al*. state "the urban heat island dominates the sea breeze effects in downtown areas," and "trends similar to those reported in [their] article may be expected in the future as coastal cities become more populated."

Velazquez-Lozada *et al*. (2006) evaluated the thermal impacts of historical land cover and land use (LCLU) changes in San Juan, Puerto Rico over the last four decades of the twentieth century by analyzing air temperatures measured at a height of approximately two meters above ground level within four different LCLU types (urban-coastal, rural-inland, rural-coastal, and urban-inland). They estimated what the strength of the urban heat island might be in the year 2050, based on anticipated LCLU changes and a model predicated on their data of the past 40 years. Their work revealed "the existence of an urban heat island in the tropical coastal city of San Juan, Puerto Rico that has been increasing at a rate of 0.06°C per year for the last 40 years." They report predicted LCLU changes between now and 2050 will lead to an urban heat island effect "as high as 8°C for the year 2050."

Noting a mass population migration from rural Mexico into medium- and large-sized cities took place throughout the second half of the twentieth century, Jáuregui (2005) examined the effect of this rapid urbanization on city air temperatures, analyzing the 1950–1990 minimum air temperature series of seven large cities with populations in excess of a million people and seven medium-sized cities with populations ranging from 125,000 to 700,000 people. Temperature trends were positive at all locations, ranging from 0.02°C per decade to 0.74°C per decade. Grouped by population, the average trend for the seven large cities was 0.57°C per decade, and the average trend for the seven mid-sized cities was 0.37°C per decade. These results, Jáuregui writes, "suggest that the accelerated urbanization process in recent decades may have substantially contributed to the warming of the urban air observed in large cities in Mexico," once again illustrating the magnitude of the urban heat island effect compared to the global warming of the past century, as well as the urban heat island's dependence on the nature of the urban landscape. This further suggests it is next to impossible to adjust surface air temperature measurements made within an urban area to the degree of accuracy required to correctly quantify background or rural climate change, which may be an order of magnitude or two smaller than the perturbing effect of the city.

Garcia Cueto *et al*. (2009) used daily records of maximum and minimum temperature from six weather stations "in Mexicali City [Mexico] and its surroundings" covering the period 1950–2000, and "a climatic network of rural and urban weather stations in Mexicali and its valley and the Imperial Valley, California" over the "contemporary period (2000–2005)," to characterize the spatial and temporal development of the city's urban heat island over the latter half of the twentieth century and the first five years of the twenty-first century. Mexicali City is located along the border of the United States at the northern end of Mexico's Baja California. It is an urban settlement that had its beginnings in the first decade of the twentieth century, when it had an area of approximately 4 km^2; by 1980 it covered a little more than 40 km^2, and by 2005 it extended over more than 140 km^2.

The researchers found Mexicali City "changed from being a cold island (1960–1980) to a heat island with a maximum intensity of 2.3°C in the year 2000, when it was compared with rural weather stations of Imperial, California," concluding "the replacement of irrigated agricultural land by urban landscapes, anthropogenic activity and population growth, appear to be the major factors responsible for the observed changes." From "more updated information (2000–2005)," they found "the greatest intensity of the urban heat island was in winter with a value of 5.7°C, and the lowest intensity in autumn with 5.0°C."

These North American studies confirm the impact of population growth on the urban heat island effect is very real and can be very large, vastly overshadowing the effects of natural temperature change. As Oke (1973) demonstrated four decades ago, towns with as few as a thousand inhabitants typically create a warming of the air within them that is more than twice as great as the increase in mean global air temperature believed to have occurred since the end of the Little Ice Age, and the urban heat islands of the great metropolises of the world create warmings that rival those that occur between full-fledged ice ages and interglacials.

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4.2.2.4 Rest of World

The previous two subsections examined the effects of urbanization on temperatures in Asia and North America. This section reviews studies examining this phenomenon in other parts of the world.

Bohm (1998) studied nine urban, suburban, and rural temperature records (three of each type, determined to be the best available on the basis of careful study from a total of 34 available records) to determine the evolving nature of the heat island of Vienna, Austria between 1951 and 1996, a 45-year period in which the city experienced zero population growth. Simultaneously, however, there was a 20 percent decrease in woodland and a 30 percent decrease in grassland within the city, as well as a doubling of the number of buildings; a tenfold increase in the number of cars; a 60 percent increase in street, pavement, and parking area; and a 2.5-fold increase in energy consumption. Bohm found the suburban stations exhibited city-induced temperature increases ranging from 0.11 to 0.21°C over the 45-year period of the study, while the urban stations experienced city-induced temperature increases ranging from zero, in the historic center of the city, to 0.6°C in the area of most intensive urban development.

Bohm writes, "the case study of Vienna illustrates the weakness inherent in studies which use only two stations to describe urban heat islands or use linear regression models to connect population directly to heat island intensity and trend." Both of these procedures are typically used in making corrections for urban heat island effects in studies of global near-surface air temperature trends. More detailed analyses of urban development characteristics are needed to correct the global temperature record of the past century to account for these phenomena.

Bottyan *et al*. (2005) examined the influence of built-up areas on the near-surface air temperature field of Debrecen, Hungary, which sits on nearly flat terrain in the Great Hungarian Plain with a population of 220,000. The researchers used mobile measurements made under different types of weather conditions between March 2002 and March 2003. The researchers found "the area of the mean maximum UHI [urban heat island] intensity of higher than 2°C is 76 times larger in the non-heating season than in the heating season (0.5% and 38% respectively)," and "the strongest developments of UHI occurring in the warmer and colder periods were 5.8°C and 4.9°C respectively." They also state they "proved a strong linear relationship between the mean UHI intensity and the urban parameters studied, such as built-up ratio and its areal extensions, in both seasons."

Hughes and Balling (1996) analyzed near-surface air temperature data from what they describe as "five very large metropolitan areas and 19 stations from non-urban locations" of South Africa for the period 1960–1990, comparing their results with those of Jones (1994) for the same time interval. The pair of scientists report the mean annual air temperature trend of the five large cities averaged 0.24°C per decade, and the mean warming rate of the 19 non-urban centers was a statistically insignificant 0.09°C per decade over the 1960–1990 period, compared to the overall warming rate of 0.31°C per decade derived by Jones for the entire country.

In addition, Hughes and Balling note, the mean rate-of-warming difference between their urban and non-urban sites was driven primarily by increases in daily minimum temperatures, which rose at a mean rate of 0.07°C per decade at the non-urban stations but an average rate of 0.34°C per decade at the five large cities. The "disparate trends in temperature" between the urban and non-urban stations "suggest that urbanization has influenced the Jones (1994) records for South Africa over the 1960–1990 period of apparent rapid warming," and "half or more of this recent warming may be related to urban growth, and not to any widespread regional temperature increase."

Torok *et al*. (2001) studied urban heat islands in several cities in Australia with populations ranging from approximately 1,000 to 3,000,000 people. They report the maximum urban-rural temperature differences of the Australian cities were found to scale linearly with the logarithms of their populations, and Torok *et al*. note the same was true for cities in Europe and North America. The heat islands of Australian cities were generally less than those of similar-size European cities (which were less than similar-size North American cities), and they increased at a slower rate with population growth than did European cities (which increased more slowly than did cities in North America). The regression lines of all three continents essentially converged in the vicinity of a population of 1,000 people, however, where the mean maximum urban-rural temperature difference was approximately 2.2 ± 0.2 °C.

The four researchers note their experimental results "were sampled during atypical conditions which were suitable for maximum urban heat island genesis," and therefore "they cannot be used to adjust long-term annual mean temperature records for urban influences." Nevertheless, they say their results imply "climatological stations in large cities should preferably be excluded from studies into long-term climate change," and "those in small towns should be located away from the town centers."

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4.1.3 Potential Problems with Climate Proxies

In addition to the errors that can affect temperature records of the modern era, such as those associated with urbanization as discussed in the previous section, several potential inaccuracies can, if not properly accounted for, adversely influence proxy temperature records of the more distant past. This section highlights some of the problems that have been identified, starting with a discussion of tree-ring proxies, as the IPCC has heavily relied on such proxies in the past.

Two tree-ring characteristics have been used to reconstruct histories of past air temperature trends around the world: tree-ring *density* and tree-ring *width*. Temperature histories derived from the first of these properties are considered to be more accurate than reconstructions based on tree-ring width, as the latter are falsely influenced by the productivity-enhancing effect of the rise in the air's CO_2 content, which has dramatically increased tree-ring widths, particularly over the past 70 years. This tree-ring growth record has been falsely attributed to a dramatic increase in air temperature, when in reality Earth has experienced no net warming over this period.

Cowling and Sykes (1999) note many methods of palaeoclimate reconstruction "are built upon the assumption that plant-climate interactions remain the same through time or that these interactions are independent of changes in atmospheric CO_2." This assumption had been challenged nearly a dozen years earlier by Idso (1989a) and a few years later by Polley *et al*. (1993). Other scientists reached the same conclusion, resulting in a sufficient volume of published research on the topic to conduct a review of it. Cowling and Sykes conducted such a review and conclude "a growing number of physiological and palaeoecological studies indicate that plant-climate interactions are likely not the same through time because of sensitivity to atmospheric CO_2." They explain "C_3-plant physiological research shows that the processes that determine growth optima in plants (photosynthesis, mitochondrial respiration, photorespiration) are all highly CO_2-dependent." Moreover, "the ratio of carbon assimilation per unit transpiration (called water-use efficiency) is sensitive to changes in atmospheric CO_2 and "leaf gas-exchange experiments indicate that the response of plants to carbon-depleting environmental stresses are strengthened under low CO_2 relative to today."

These phenomena combine to produce dramatic increases in plant growth and water use efficiency with increases in the air's CO_2 content. Such increases in vegetative vigor had been interpreted (to the date of their writing) almost exclusively not in terms of atmospheric CO_2 variations but in terms of changes in air temperature and/or precipitation. Therefore, all previous plant-based climate reconstructions for a period of time over which the air's CO_2 content had experienced a significant change must have been in error to some degree unless they accounted for the growth-enhancing effects of the CO_2 increase, which none had yet done, except LaMarche *et al*. (1984) and Graybill and Idso (1993).

Many scientists (including the IPCC) had been using long-term tree-ring chronologies—specifically, Mann *et al*. (1998, 1999)—to create a climate history of Earth that exhibits dramatic late-twentieth century warming that was likely far too great. As Briffa (2000) explains, the recent high growth rates of the trees in these chronologies "provide major pieces of evidence being used to assemble a case for anomalous global warming, interpreted by many as evidence of anthropogenic activity." However, he continues, "the empirically derived regression equations upon which our reconstructions are based may be compromised if the balance between photosynthesis and respiration is changed" by anything other than air temperature. And as Cowling and Sykes conclude, "implicit in the assumption that plant-climate relationships remain the same through time is the notion that temperature-plant interactions are independent of changes in atmospheric CO_2, which is not supported by physiological data."

The flawed studies of Mann *et al*. fast became the centerpiece (Crowley, 2000; Mann, 2000) of the IPCC's characterization of current climate, professing to show what they misguidedly concluded was an unusual and unprecedented rise in late-twentieth century temperatures, which they concluded to be largely the product of CO_2-induced global warming.

In another review paper conducted nearly a decade later, D'Arrigo *et al*. (2008) dissected this *divergence problem*, which they describe as "an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings," assessing the possible causes and implications of the phenomenon.

The four researchers identified more than a dozen possible causes of the problem: moisture stress, non-linear or threshold responses to warming, local pollution, delayed snowmelt, changes in seasonality, differential responses to maximum and minimum temperatures, global dimming, methodological issues related to "end effects," biases in instrumental target data, the modeling of such data, declining stratospheric ozone concentrations, increased UV-B radiation at ground level, and "an upward bias in surface thermometer temperature measurements in recent years related to heat island effects."

D'Arrigo *et al*. note "reconstructions based on northern tree-ring data impacted by divergence cannot be used to directly compare past natural warm periods (notably, the Medieval Warm Period) with recent 20th century warming, making it more difficult to state unequivocally that the recent warming is unprecedented." With respect to a resolution of the issue, they state their review "did not yield any consistent pattern that could shed light on whether one possible cause of divergence might be more likely than others," leading them to conclude "a combination of reasons may be involved that vary with location, species or other factors, and that clear identification of a sole cause for the divergence is probably unlikely." Such findings suggest it is premature to claim, as the IPCC does, that recent warming is unprecedented over the past millennium or more, particularly on the basis of tree-ring width data.

In another paper examining the potential influence of atmospheric carbon dioxide on proxy records Gonzales *et al*. (2008) write, "there has been a growing awareness that past variations in CO_2 may have globally influenced plant physiology, vegetation composition, and vegetation structure (Idso, 1989b; Cowling, 1999; Cowling and Sykes, 1999; Wu *et al*., 2007a,b)." They also note "this information has spurred a debate over the relative importance of CO_2 versus climate as drivers of Quaternary vegetation change." Gonzales *et al*. compared simulated and pollen-inferred leaf area index (LAI) values with regional vegetation histories of northern and eastern North America "to assess both data and model accuracy and to examine the relative influences of CO_2 and climate on vegetation structure over the past 21,000 years." They made use of BIOME4, "a biogeochemistry-biogeography equilibrium vegetation model (Kaplan, 2001)" that "was designed in part for paleo-vegetation applications, and has been widely used to simulate vegetation responses to late-Quaternary CO_2 and climates." Concurrently, and "to provide paleo-climate scenarios for the BIOME4 simulations," the three researchers "used surface temperature, precipitation and cloudiness values from a series of Hadley Centre Unified Model simulations."

Gonzales *et al*. note theirs was the first study "to use both BIOME4 simulations and pollen-based reconstructions to develop detailed Quaternary LAI histories for North America," and they report their "BIOME4 sensitivity experiments indicated that climate was the primary driver of late-Quaternary changes in LAI in northern and eastern North America, with CO_2 a secondary factor." More importantly, Gonzales *et al*. observed their work "emphasizes the need for models to incorporate the effects of both CO_2 and climate on [the reconstruction of] late-Quaternary vegetation dynamics and structure." Vegetation-based climate reconstructions must incorporate the biological effects of changes in atmospheric CO_2 concentration, especially when attempting to compare late-twentieth century reconstructed temperatures with reconstructed temperatures of the Roman and Medieval Warm Periods and the Holocene Climatic Optimum. Until this deficiency is corrected, truly valid comparisons between these earlier times and the present cannot be made based on tree-ring width data.

Knapp and Soule (2008) examined recent radial growth increases in western juniper trees (*Juniperus occidentalis* var. *occidentalis* Hook.) based on their analysis of a master tree-ring chronology dating from AD 1000–2006, developed from 11 semi-arid sites in the interior U.S. Pacific Northwest that had experienced minimal anthropogenic influence other than that provided by the historical increase in the air's CO_2 content that is everywhere present.

They then used measured climate data for the period 1907–2006 to determine which climatic parameter tree radial growth was most responsive to: temperature, precipitation, or drought severity, as represented by the Palmer Drought Severity Index (PDSI) for the month of June. They found June PDSI to be the most important factor, explaining fully 54 percent of annual radial growth variability. When they added CO_2 as a second predictive factor, they found it "accounted for a 14% increase in explanatory power." In addition, they report, "use of the PDSI-only regression model produced almost exclusively positive residuals since 1977," but "the +CO_2 model has a greater balance of positive (53%) and negative residuals over the same period." They conclude, "climatic reconstructions based on pre-1980 data would not be significantly influenced by rising CO_2 levels," but reconstructions produced after that time would be.

During the period 1977–2006, which Knapp and Soule describe as being "unlike any other period during the last millennium," the late-twentieth century/early-twenty-first century radial growth of the western juniper trees was 27 percent greater than the long-term (AD 1000–2006) average. That growth could not have been caused by any increase in air temperature, for they report "western juniper responds negatively to temperature, negating any linkages to regional warming." Neither could the anomalous growth increase have been due to anomalous nitrogen fertilization, for the two researchers note "the eleven chronology sites do not fall under any of the criteria used to identify ecosystems significantly impacted by N-deposition," citing the work of Fenn *et al*. (2003). They were left to conclude the growth increase was likely due to the increase in the air's CO_2 content over the latter period.

Esper *et al*. (2005) weigh in on why there are differences among climate reconstructions and what it would take to reduce present uncertainties to gain a more complete and correct understanding of temperature changes over the past thousand years. The six scientists note we generally understand the shape of long-term climate fluctuations better than their amplitudes. For instance, nearly all 1,000-year temperature reconstructions capture the major climatic episodes of the Medieval Warm Period, Little Ice Age, and Current Warm Period, but for various reasons they exhibit differences in the degree of climatic warming or cooling experienced in the transitions between them, which for decadal means may amount to as much as 0.4 to 1.0°C. They suggest the discrepancies might be reduced by reducing the calibration uncertainty among the proxies, ensuring the accurate preservation and assessment of low-to-high frequency variation in proxy data, using appropriate frequency bands to best fit instrumental data, avoiding the use of regional tree-ring and other paleo records in which long-term trends (low-frequency variations) are not preserved, selecting instrumental data with which to compare proxy records to avoid incorrect alterations to the observational data that can result from homogeneity adjustments and methodological differences, and obtaining more proxy data that cover the full millennium and represent the same spatial domain as the instrumental target data (e.g., hemisphere).

In an important paper published in the peer-reviewed journal *Climatic Change*, Swiss scientists Jan Esper (of the Swiss Federal Research Institute) and David Frank (of the Oeschger Centre for Climate Change Research) took the Intergovernmental Panel on Climate Change (IPCC) to task for concluding in its *Fourth Assessment Report* (AR4) that, relative to modern times, there was "an increased heterogeneity of climate during medieval times about 1000 years ago."

This finding, if true, would be of great significance to the ongoing debate over the cause of twentieth century global warming, because, Esper and Frank write, "heterogeneity alone is often used as a distinguishing attribute to contrast with present anthropogenic warming." If the IPCC's contention is false, it would mean the warmth of the Current Warm Period is not materially different from that of the Medieval Warm Period, suggesting there is no need to invoke anything extraordinary (such as anthropogenic

CO_2 emissions) as the cause of Earth's current warmth.

With mathematical procedures and statistical tests, Esper and Frank demonstrated the records reproduced in the AR4 "do not exhibit systematic changes in coherence, and thus cannot be used as evidence for long-term homogeneity changes." And even if they could be thus used, they note "there is no increased spread of values during the MWP," and the standard error of the component datasets "is actually largest during recent decades." Consequently, the researchers conclude, their "quantification of proxy data coherence suggests that it was erroneous [for the IPCC] to conclude that the records displayed in AR4 are indicative of a heterogeneous climate during the MWP." The IPCC's conclusion appears even more erroneous today in light of the hundreds of papers discussed in Section 4.2.2 that collectively demonstrate the homogeneity of a global MWP.

There are additional challenges in quantifying historical temperatures from other proxy methods. Correia and Safanda (1999) reviewed a set of 20 temperature logs derived from boreholes located at 14 sites in the small region of mainland Portugal in an attempt to reconstruct a five-century surface air temperature history for that part of the world, which proved to be a difficult task. Seven of the borehole temperature logs were too "noisy" to use, and six displayed evidence of groundwater perturbations and were thus not usable. Of the remaining seven logs, all depicted little temperature change over the first three centuries of record. Thereafter, four exhibited warming trends that began about 1800 and peaked around 1940, one showed a warming that peaked in the mid-1800s, another was constant across the entire five centuries, and one revealed cooling over the last century. These differences are surprising considering the relatively small distance separating the borehole locations. The two researchers conclude "the single inversions cannot be interpreted individually."

Correia and Safanda next performed a joint analysis of the seven usable borehole records, obtaining a warming of 0.5–0.6°C since the second half of the eighteenth century, followed by a cooling of 0.2°C. They compared the joint borehole record with the surface air temperature record directly measured at a meteorological station in Lisbon, about 150–200 km to the northwest. From the beginning of the surface air temperature record in 1856 until 1949, the Lisbon data yielded a warming of 0.8°C, whereas the borehole record displayed a warming of only 0.3–0.4°C.

The two temperature histories could both be right, but they also could both be wrong. The Lisbon record, for example, could suffer from urban heat island-type problems, and the joint borehole record was obtained only after several individual records were rejected for various reasons and a number of simplifying assumptions were invoked in the analyses of the remaining records. The authors reluctantly recognize these problems, noting the issue was not yet resolved and much more work needed to be done to arrive at a satisfactory conclusion. This study demonstrates several common difficulties in deriving borehole temperature records.

Bodri and Cermak (2005) note temperature profiles derived from borehole records had been increasingly used to obtain proxy climate signals at various locations across the surface of Earth. They caution the techniques employed in reconstructing pre-observational (pre-instrumental era) mean temperatures from borehole data suffer from certain limitations, one of the major ones being the presence of underground fluids that can distort the true climatic signal (Lewis and Wang, 1992). Bodri and Cermak thus developed a corrective measure to account for vertical conductive and advective heat transport in a 1-D horizontally layered stratum—as opposed to the then-popular purely conductive approach—which they proceeded to apply to four borehole records drilled near Tachlovice in the Czech Republic.

The duo's analyses of the four borehole temperature logs revealed the conductive/advective approach was far superior to the purely conductive approach, explaining 83 to 95 percent of the temperature signal where the purely conductive model could explain no more than 27 to 58 percent. In addition, the purely conductive approach was found to underestimate the pre-observational mean temperature by 0.3 to 0.5°C. This underestimate produces a significant overestimate of the degree of warming experienced from the pre-observational period to the present. The two scientists also report both of the pre-observational mean temperature values for eighteenth-century Bohemia (the one derived from the conductive/advective approach and the one derived from the purely conductive approach) "exceed the annual temperatures characteristic for the 19th/20th centuries," which "may indicate that the warming has still not achieved its earlier (late 18th century) level."

Considering another type of possible proxy error, Darling *et al*. (2000) reported on their examination of the genetic variation in the small subunit ribosomal

RNA gene of three morphospecies of planktonic foraminifera from Arctic and Antarctic subpolar waters, which led to the discovery that foraminiferal morphospecies can consist of a complex of genetic types. They found each "species," as these entities previously had been designated, was composed of three to five distinct genetic varieties that could be classified as individual species themselves. The morphological, chemical, and stable-isotope differences associated with the calcitic shells of the three morphospecies they studied are used extensively by palaeoceanographers for purposes of climate reconstruction, based on the assumption that each morphospecies represents a genetically continuous species with a single environmental/habitat preference. They write, "if this is not the case"—as indicated by their study and others—"stable-isotope and geochemical analyses of planktonic foraminiferal shells, and census-based transfer-function techniques derived from such pooled data, must include significant noise, if not error." As more is learned about the diversity of these biotic climate indicators, it is likely certain additional palaeoclimatic histories will have to be revised.

Cohn and Lins (2005) analyzed statistical trend tests of hydroclimatological data such as discharge and air temperature in the presence of long-term persistence (LTP), in order to determine what LTP, if present, implied about the significance of observed trends. They determined "the presence of LTP in a stochastic process can induce a significant trend result when no trend is present, if an inappropriate trend test is used." They also note, "given the LTP-like patterns we see in longer hydroclimatological records ... such as the periods of multidecadal drought that occurred during the past millennium and our planet's geologic history of ice ages and sea level changes, it might be prudent to assume that hydroclimatological processes could possess LTP." They add "nearly every assessment of trend significance in geophysical variables published during the past few decades has failed to account properly for long-term persistence."

In discussing the implications of their work with respect to temperature data, Cohn and Lins note there is overwhelming evidence the planet has warmed during the past century. However, they ask, "could this warming be due to natural dynamics?" They state, "given what we know about the complexity, long-term persistence, and non-linearity of the climate system, it seems the answer might be yes." Although reported temperature trends may be real, they note, those trends also may be insignificant. Cohn and Lins say this leads to "a worrisome possibility": that "natural climatic excursions may be much larger than we imagine, ... so large, perhaps, that they render insignificant the changes, human-induced or otherwise, observed during the past century."

Another potential problem with paleoclimate proxies was identified by Loehle (2004), who used a pair of 3,000-year-long proxy climate records with minimal dating errors to characterize the pattern of climate change over the past three millennia in a paper that provides the necessary context for properly evaluating the cause or causes of twentieth century global warming.

The first of the two temperature series was the sea surface temperature (SST) record of the Sargasso Sea, derived by Keigwin (1996) from a study of the oxygen isotope ratios of foraminifera and other organisms contained in a sediment core retrieved from a deep-ocean drilling site on the Bermuda Rise. This record provided SST data for about every 67th year from 1125 BC to AD 1975. The second temperature series was the ground surface temperature record derived by Holmgren *et al*. (1999, 2001) from studies of color variations of stalagmites found in a cave in South Africa, which variations are caused by changes in the concentrations of humic materials entering the region's groundwater that have been reliably correlated with regional near-surface air temperature.

Explaining why he used these two specific records and only these two records, Loehle writes, "most other long-term records have large dating errors, are based on tree rings, which are not reliable for this purpose (Broecker, 2001), or are too short for estimating long-term cyclic components of climate." Also, in a repudiation of the approach employed by Mann *et al*. (1998, 1999) and Mann and Jones (2003), he states, "synthetic series consisting of hemispheric or global mean temperatures are not suitable for such an analysis because of the inconsistent timescales in the various data sets." In addition, his testing indicates "when dating errors are present in a series, and several series are combined, the result is a smearing of the signal."

Loehle reports "a comparison of the Sargasso and South Africa series shows some remarkable similarities of pattern, especially considering the distance separating the two locations," and he states this fact "suggests that the climate signal reflects some global pattern rather than being a regional signal only." He also notes a comparison of the mean record with the South Africa and Sargasso series from which it was derived "shows excellent agreement" and "the patterns match closely," concluding, "this would not be the case if the two series were independent or random."

Proceeding with his approach of fitting simple periodic models to the temperature data as functions of time, with no attempt to make the models functions of solar activity or any other physical variable, Loehle fit seven time-series models to the two temperature series and to the average of the two series, using no data from the twentieth century. In all seven cases, he reports good to excellent fits were obtained. As an example, the three-cycle model he fit to the averaged temperature series had a simple correlation of 0.58 and an 83 percent correspondence of peaks when evaluated by a moving window count.

Comparing the forward projections of the seven models through the twentieth century leads directly to the most significant conclusions of Loehle's paper. He first notes six of the models "show a warming trend over the 20th century similar in timing and magnitude to the Northern Hemisphere instrumental series," and "one of the models passes right through the 20th century data." These results clearly suggest, in his words, "20th century warming trends are plausibly a continuation of past climate patterns" and, therefore, "anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes."

Loehle's analyses also reveal a long-term linear cooling trend of 0.25°C per thousand years since the peak of the interglacial warm period that occurred some 7,000 years ago, essentially identical to the mean value of this trend derived from seven prior assessments of its magnitude and five prior climate reconstructions. In addition, Loehle's analyses reveal the existence of the Medieval Warm Period of AD 800–1200, which is shown to have been significantly warmer than the Current Warm Period Earth has experienced so far, as well as the existence of the Little Ice Age of AD 1500–1850, which is shown to have been the coldest period of the entire 3,000-year record.

As corroborating evidence for the global nature of these major warm and cold intervals, Loehle cites 16 peer-reviewed scientific journal articles that document the existence of the Medieval Warm Period in all parts of the world and 18 articles that document the worldwide occurrence of the Little Ice Age. In addition, both the Sargasso Sea and South African temperature records reveal the existence of a major temperature spike that began sometime in the early 1400s (though Loehle makes no mention of this feature in his paper). This abrupt warming pushed temperatures considerably above the peak warmth of the twentieth century before falling back to pre-spike levels in the mid-1500s, providing support for the similar finding of higher-than-current temperatures in that time interval by McIntyre and McKitrick (2003) in their reanalysis of the data Mann *et al*. used to create their controversial "hockey stick" temperature history, which gives no indication of the occurrence of this high-temperature regime.

The models developed by Loehle confirm the existence of three climate cycles previously identified by others. In his seventh model, for example, there is a 2,388-year cycle he describes as comparing "quite favorably to a cycle variously estimated as 2,200, 2,300, and 2,500 years (Denton and Karlen, 1973; Karlen and Kuylenstierna, 1996; Magny, 1993; Mayewski *et al*., 1997)." In addition, there is a 490-year cycle that likely "corresponds to a 500-year cycle found previously (e.g. Li *et al*., 1997; Magny, 1993; Mayewski *et al*., 1997)" and a 228-year cycle that "approximates the 210-year cycle found by Damon and Jirikowic (1992)."

Loehle concludes, "solar forcing (and/or other natural cycles) is plausibly responsible for some portion of 20th century warming" or, as he indicates in his abstract, maybe even all of it.

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4.2 The Non-Uniqueness of Current Temperatures

The IPCC has long asserted CO_2-induced global warming accelerated significantly over the twentieth century and is unprecedented in the past millennium or more. However, as shown in the preceding section of this chapter, the temperature datasets upon which these claims are based are likely contaminated with errors of sufficient magnitude to render that assessment questionable at best.

The following section evaluates the correctness of the IPCC's claim. If temperatures of the past millennia—when atmospheric CO_2 concentrations were 30 percent lower than they are now—were as warm as or warmer than the present, then it must be recognized there is nothing unusual or unnatural about the planet's current level of warmth. This would invalidate the IPCC's claims that "it is *extremely likely* that human activities have caused most of (at least 50%) the observed increase in global average temperatures since the 1950s" and "it is *virtually certain* that this warming is not due to internal variability alone" (Second Order Draft of AR5, dated October 5, 2012, p. 10-3).

Our review of the literature, highlighted in the subsections below, reveals many scientists have indeed presented evidence of *multiple* prior warm periods around the world. Much of this work focuses on a period of warmth about a thousand years ago, but some studies identify multiple periods throughout the Holocene when it was warmer than the present, at much lower atmospheric CO_2 concentrations. We begin with a discussion of current temperatures within the longer-term context of the past few interglacial climates.

4.2.1 The Warmth of Prior Interglacial Climates

Throughout Earth's geologic history, major ice ages have occurred repeatedly, with ten affecting the planet in the past one million years and another ten in the million or so years before that. Each persists for about 90,000 years, after which it is followed by an approximate 10,000-year interglacial.

Our understanding of climatic conditions during glacial–interglacial cycles is limited, but a constant flow of new studies is providing additional information about the topic. This growing body of knowledge provides a long historical baseline against which the current state of Earth's climate may be compared, enabling a better understanding of the significance of current climate trends and their causes.

Some scientists have claimed the ongoing rise in the air's CO_2 content made the decade of the 1990s the warmest period of the entire past millennium (Mann *et al*., 1998, 1999). "Unprecedented" is the word proponents of this idea routinely use to describe the current temperature of the globe. However, when the mean temperature of the 1990s or 2000s is compared with the warmest temperatures of the four prior interglacials (for which we have high-quality reconstructed temperature records), the two decades are found to have been much cooler than *all* of these other periods.

Petit *et al*. (1999), for example, analyzed an ice core recovered from the Russian Vostok drilling station in East Antarctica, from which they extracted a 420,000-year history of Earth's near-surface air temperature and atmospheric CO_2 concentration (see Figure 4.2.1.1). This record covered the current interglacial period, the Holocene, and the preceding four such climatic intervals. This record is important for what it reveals about the uniqueness or non-uniqueness of the Holocene: The current interglacial is by far the coldest of the five most recent such periods. The four interglacials that preceded the Holocene were, on average, more than 2°C warmer than the one in which we currently live. Also, atmospheric CO_2 concentrations during all four prior interglacials never rose above approximately 290 ppm, whereas the air's CO_2 concentration in mid-2013 stood at about 400 ppm. If there was anything unusual, unnatural, or unprecedented about late-twentieth century air temperatures, it is that they were so *low* in the presence of such *high* CO_2 concentrations.

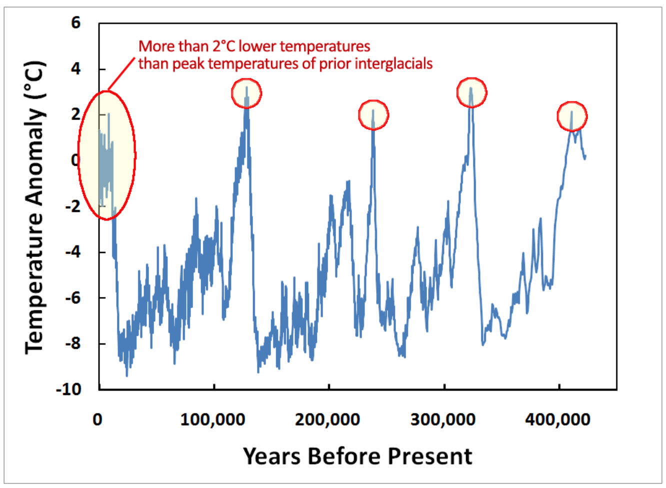

Figure 4.2.1.1. A 420,000-year history of Earth's near-surface air temperature extracted from an ice core recovered from the Russian Vostok drilling station in East Antarctica, revealing temperatures of the present are more than 2°C cooler than peak temperatures of all four prior interglacials. Adapted from Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M.., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436..

Similar findings have been obtained from the Dome Fuji ice core, extracted from a site in an entirely different sector of East Antarctica that is separated from the Vostok ice core site by 1,500 km (Watanabe *et al*., 2003). Although of somewhat shorter duration, covering only the past three glacial-interglacial periods (marine stages 5.5, 7.5, and 9.3), this independent proxy temperature record also reveals the past three interglacials, in the words of Watanabe *et al*., "were much warmer than the most recent 1,000 years (~4.5°C for stage 5.5 and up to 6°C for stage 9.3)."

This prior interglacial warmth is also evident in a 550,000-year sea surface temperature (SST) dataset derived by Herbert *et al*. (2001) from marine sediment cores obtained along the western coast of North America, from around 22°N latitude at the southern tip of the Baja Peninsula to around 42°N latitude off the coast of Oregon. According to this reconstructed SST dataset, the nine researchers who developed it write, "the previous interglacial (isotope stage 5e) produced surface waters several degrees warmer than today," such that "waters as warm as those now at Santa Barbara occurred along the Oregon margin." Their data show SSTs for this region in the current interglacial have not reached the warm peaks witnessed in all four of the preceding interglacial periods, falling short by 1 to 4°C.

Thus, over the past half-million years and within the context of the most recent five full interglacials, it is clear the average near-surface air temperature of Earth during the 1990s was not unusually warm, but unusually *cool*, despite the 1990s' much greater atmospheric CO_2 content.

These observations suggest Earth's current temperature is not indicative of dangerous human interference with the planet's thermoregulatory system. The IPCC's claim of a human influence on today's climate is based solely on its contention that Earth's current temperature is uncommonly high (Crowley, 2000), when it clearly is not. Earth was significantly warmer than it is today in all of the preceding interglacials for which we have good temperature data, and it is highly implausible to attribute those high temperatures of the past to human influence or even natural increases in the air's CO_2 content, which during the four previous interglacials never rose above approximately 290 ppm.

The supposed causal relationship between Earth's atmospheric CO_2 concentration and global temperature has been further weakened by the work of Fischer *et al*. (1999), Indermuhle *et al*. (1999), and Stephens and Keeling (2000). Fischer *et al*. examined records of atmospheric CO_2 and air temperature derived from Antarctic ice cores across a quarter of a million years. Over this time span, the three most dramatic warming events were those associated with the terminations of the past three ice ages, and for each of these global warmings, Earth's air temperature rose well *before* any increase in atmospheric CO_2. The air's CO_2 content did not begin to rise until 400 to 1,000 years *after* the planet began to warm. Increases in the air's CO_2 content did not trigger these massive changes in climate.

In addition, during a 15,000-year period following one of the glacial terminations the air's CO_2 content was essentially constant but air temperatures dropped to values characteristic of glacial times. Also, just as increases in atmospheric CO_2 did not trigger any of the major global warmings that ended the past three ice ages, neither was the induction of the most recent ice age driven by a decrease in CO_2. And when the air's CO_2 content finally did begin to drop after the last ice age was fully established, air temperatures either remained fairly constant or rose, doing just the opposite of what climate models suggest should have happened if changes in atmospheric CO_2 drive changes in climate.

Indermuhle *et al*. (1999) determined the CO_2 content of the air gradually rose after the termination of the last great ice age, by approximately 25 ppm in almost linear fashion between 8,200 and 1,200 years ago, in a time of slow but steady *decline* in global air temperature—again just the opposite of what would be expected if changes in atmospheric CO_2 affect climate in the way suggested by the popular CO_2-greenhouse effect theory.

Another problem for this theory arises from the work of Stephens and Keeling (2000), who in a study of the influence of Antarctic sea ice on glacial-interglacial CO_2 variations proposed a mechanism to explain the observed synchrony between Antarctic temperature and atmospheric CO_2 concentration during glacial-interglacial transitions. Their mechanism presumes temperature is the independent variable that alters sea ice extent, which then alters the sea-to-air CO_2 flux in the high-latitude region of the Southern Ocean and consequently changes the CO_2 content of the atmosphere. In their explanation for the gross correlation of CO_2 and air temperature over glacial-interglacial cycles, atmospheric CO_2 variations are clearly the result of temperature variations, not vice versa. (For a more in-depth discussion on the leads and lags of the historic temperature/CO_2 relationship, see Chapter 2.)

Ding *et al*. (1999) developed a high-resolution record of climate changes over the past two glacial-interglacial cycles based on a study of grain sizes in soil cores removed from sections of the northwestern part of the Chinese Loess Plateau. The scientists detected the presence of large-amplitude millennial-scale climatic oscillations over both of the previous glacial periods, but very little such variation during the prior interglacial. Greater climatic stability during warmer interglacial periods also has been reported by Shemesh *et al*. (2001) and Alley (2000). Because interglacials appear to be more climatically stable than cooler glacial periods, we will likely not experience a significant increase in extreme weather events of the type routinely predicted by climate alarmists to accompany global warming, such as rapid climate changes of the type suggested to become more likely by Alley *et al*. (2002, 2003).

Across the long history of glacial-interglacial cycles, there is little doubt the atmosphere's CO_2 concentration is strongly correlated with its temperature, as has been demonstrated by numerous scientific studies (Petit *et al*., 1999; Augustin *et al*., 2004; Siegenthaler *et al*., 2005). Nor is there any doubt changes in air temperature generally occur anywhere from 800 to 2,800 years *before* changes in the air's CO_2 content, as is demonstrated by even more studies (Fischer *et al*., 1999; Monin *et al*., 2001; Caillon *et al*., 2003; Siegenthaler *et al*., 2005). But the evidence shows carbon dioxide cannot be the primary cause of glacial-interglacial temperature changes, nor is it likely a significant amplifier of them.

Antarctic ice core data suggest the air's current CO_2 concentration is some 40 percent higher than it was at any other time in the past 650,000 years (Siegenthaler *et al*., 2005), and its current methane concentration is approximately 130 percent higher (Spanhi *et al*., 2005)—values some scientists have referred to as "geologically incredible." If the IPCC and others were correct in attributing tremendous warming power to these two greenhouse gases, Earth should be experiencing incredibly high temperatures compared to those of prior interglacial periods. Yet this is not the case.

Greenland and Antarctica ice core data, in particular, suggest the mean recent temperature of the current interglacial, the Holocene, was not incredibly higher than temperatures reached during the past four interglacials, the earliest of which is believed to have been nearly identical to the Holocene in terms of Earth's orbit around the Sun. The mean recent temperature of the Holocene did not exceed temperatures reached during *any* of the four prior interglacials, by even a fraction of a degree. On the contrary, the mean recent temperature of the Holocene was lower. The work of Petit *et al*. referred to earlier suggests the mean recent temperature of the Holocene was more than 2°C lower than the highest temperatures of the prior four interglacials, while another analysis of the subject (Sime *et al*., 2009) suggests the "maximum interglacial temperatures over the past 340,000 years were between 6.0°C and 10.0°C above present-day values."

The empirical observations cited above reveal a relationship opposite of what is expected if carbon dioxide and methane were the powerful greenhouse gases the IPCC claims them to be. Clearly, if there is anything at all that is unusual, unnatural, or unprecedented about Earth's current surface air temperature, it is that it is so *cold*.

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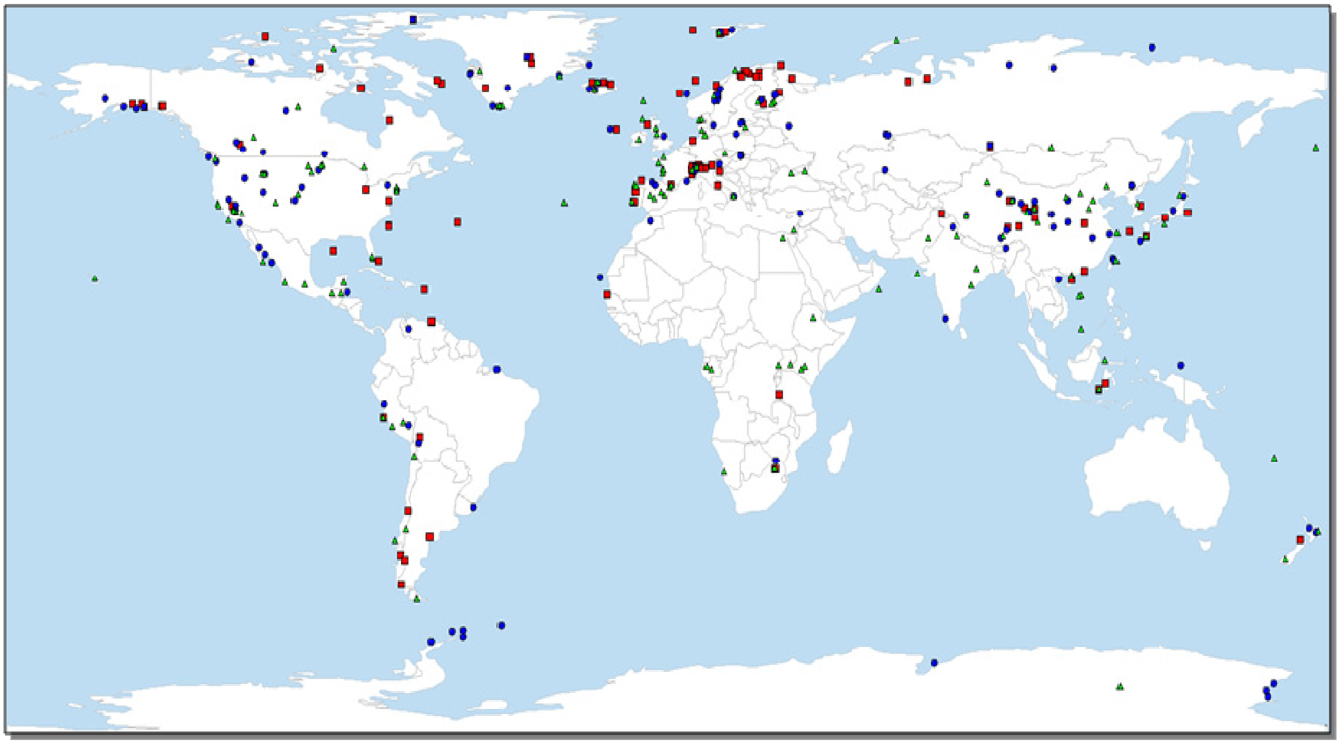

Figure 4.2.2.1. Plot of the locations of proxy climate studies for which (a) quantitative determinations of the temperature difference between the MWP and CWP can be made (red squares), (b) qualitative determinations of the temperature difference between the MWP and CWP can be made (blue circles), and (c) neither quantitative nor qualitative determinations can be made, with the studies simply indicating the Medieval Warm Period did indeed occur in the studied region (green triangles).

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4.2.2 A Global Medieval Warm Period

After initially acknowledging in its *First Assessment Report* the existence of a several-hundred-year global Medieval Warm Period (MWP) centered about a thousand years ago, during portions of which temperatures were often warmer than those of the present, the IPCC has since backtracked in succeeding reports. In its latest report (*Fifth Assessment*), for example, the IPCC states:

> In contrast to the late 20th century there is *high confidence* that the Medieval Climate Anomaly was not characterized by a pattern of higher temperatures that were consistent across seasons and regions (Second Order Draft of AR5, dated October 5, 2012, p. 5-4)

As demonstrated in this subsection and those that follow, there is in fact an enormous body of literature that clearly demonstrates the IPCC is wrong in its assessment of the MWP. The degree of warming and climatic influence during the MWP varied from region to region, and hence its consequences were manifested in a variety of ways. But that it occurred and was a global phenomenon is certain, and there are literally hundreds of peer-reviewed scientific articles that certify this truth.

In what is likely the largest synthesis of MWP research articles in the world, *CO_2 Science* (http://www.co2science.org/data/mwp/mwpp.php) has highlighted more than 350 peer-reviewed research papers documenting the global nature of this warm-temperature era.

Figure 4.2.2.1 illustrates the spatial distribution of the proxy climate studies analyzed by *CO_2 Science* according to three different categories. The first of these categories, denoted by the red squares, is comprised of studies where the scientists who conducted the work provided quantitative data that enable a determination of the degree by which the peak temperature of the MWP differed from the peak temperature of the Current Warm Period (CWP). The second category (blue circles) is comprised of studies where the scientists who conducted the work provided qualitative data that enable a determination of which of the two periods was warmer, but not by how much. The third category (green triangles) comprises studies where the MWP was evident in the study's data but the data did not provide a means by which the warmth of the MWP could be compared with that of the CWP. Such studies contradict the claim that the MWP, if it occurred at all, was only a regional phenomenon experienced by lands significantly influenced by the North Atlantic Ocean. This category also includes some studies based on data related to parameters other than temperature, such as precipitation. These studies help define the timeframe of the MWP, but they are not employed to infer anything about either its quantitative or qualitative thermal strength. Figure 4.2.2.1 reveals the truly global nature of this phenomenon.

With respect to how consistent the MWP was in time, of the 379 studies examined by *CO_2 Science*, 371 overlapped during the period 900–1200 AD. This number dips slightly to 365 if the time window is reduced to the period 1000–1200 AD, and to 337 if it is shortened further to the one hundred year period between 1000 and 1100 AD. A basic histogram of the timeframe (start year to end year) associated with the MWP of all the studies plotted in Figure 4.2.2.1 reveals the peak timeframe occurred around 1050 AD, within a more generalized 800 to 1300 AD warm era generally attributed to the MWP.

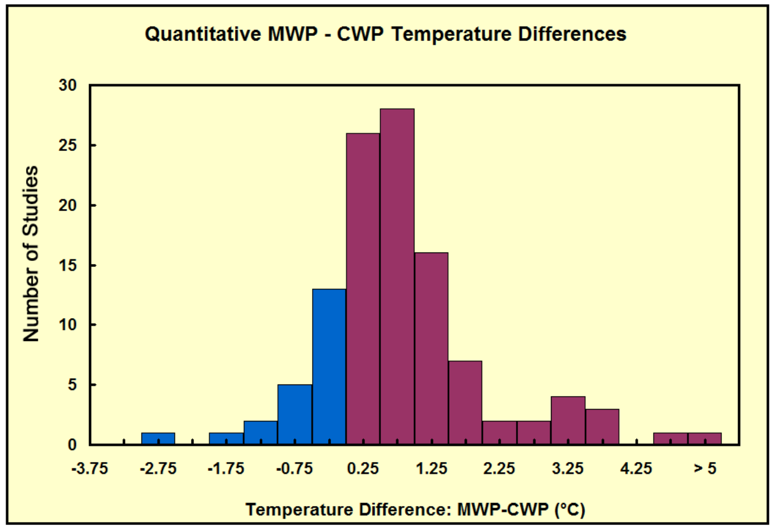

Figure 4.2.2.2. The distribution, in 0.5°C increments, of studies that allow the identification of the degree by which peak Medieval Warm Period temperatures either exceeded (positive values, red) or fell short of (negative values, blue) peak Current Warm Period temperatures.

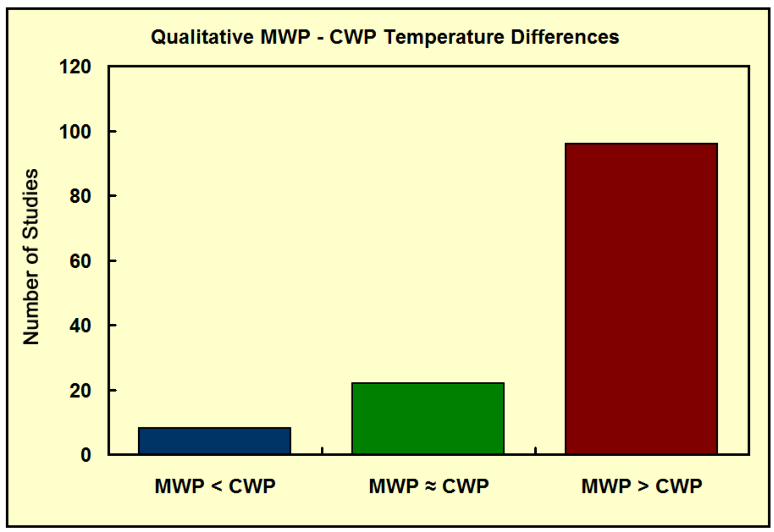

Figure 4.2.2.3. The distribution of studies that allow a qualitative determination of whether peak Medieval Warm Period temperatures were warmer than (red), equivalent to (green), or cooler than (blue) peak Current Warm Period temperatures.

As to how warm it likely was during this period, Figure 4.2.2.2 presents a plot of the frequency distribution of all MWP-CWP temperature differentials from all quantitative studies (red squares) shown in Figure 4.2.2.1. As Figure 4.2.2.2 reveals, some studies found the MWP to have been cooler than the CWP (blue columns), but the vast majority of the temperature differentials are positive (red columns), indicating the MWP was warmer than the CWP. The average of all such differentials is 0.91°C, while the median is 0.70°C.

The greater warmth of the MWP can be generalized further by analyzing the qualitative studies in Figure 4.2.2.1, which is illustrated in Figure 4.2.2.3. Here, the numbers of studies in Figure 4.2.2.1 in which the MWP was warmer than, cooler than, or about the same as, the CWP are plotted, based on actual data presented by the authors of the original works. Again, a few studies found the MWP to have been cooler than the CWP, and a few found them to be of approximately the same warmth, but the majority of studies find the MWP to have been warmer than the CWP.

The existence of a global period of warmth in Earth's recent past comparable to that of the present indicates there is nothing unusual, unnatural, or unprecedented about the warmth of the post-1950 CWP. It is not surprising that there would be a significant warming of the globe at the conclusion of what was likely the coldest period of the entire Holocene (the Little Ice Age). Thus there is no compelling reason to believe twentieth century warming (which essentially ceased about 15 years ago) is a manmade phenomenon produced by the burning of coal, gas, and oil. The CWP is much more likely to be merely the most recent phase of the natural millennial-scale oscillation of Earth's climate that has been shown to operate throughout glacial and interglacial periods alike. And since the air's CO_2 concentration has risen by some 40 percent since the MWP, and Earth is no warmer now than it was then, there is no compelling reason to conclude any of Earth's current warmth is being caused by the increase in the atmosphere's CO_2 content.

We continue our analysis of the MWP by summarizing individual research papers on the subject, which together confirm the conclusions presented above.

Initial work from Lamb (1977, 1984, 1988) and Grove (1988) suggest Earth's average global temperature may have been warmer between the tenth and fourteenth centuries AD than it is today. The existence of this Medieval Warm Period initially was deduced from historical weather records and proxy climate data from England and Northern Europe. The warmer conditions of that era are known to have had a largely beneficial impact on Earth's plant and animal life. The environmental conditions of this time period have been determined to have been so favorable that it was often referred to as the Little Climatic Optimum (Imbrie and Imbrie, 1979; Dean, 1994; Petersen, 1994; Serre-Bachet, 1994; Villalba, 1994).

The degree of warming associated with the Medieval Warm Period varied from region to region, and its consequences were manifested in a variety of ways (Dean, 1994). In Europe, temperatures reached some of the warmest levels of the past 4,000 years, allowing enough grapes to be successfully grown in England to sustain an indigenous wine industry (Le Roy Ladurie, 1971). Horticulturists in China extended their cultivation of citrus trees and perennial herbs further and further northward, resulting in an expansion of their ranges that reached its maximum extent in the thirteenth century (De'er, 1994). It has been estimated annual mean temperatures in the region must have been about 1.0 °C higher than at present, with extreme January minimum temperatures fully 3.5 °C warmer than they are today (De'er, 1994).

In North America, tree-ring chronologies from the southern Canadian Rockies provide evidence for higher treelines and wider ring-widths between AD 950 and 1100, suggesting warmer temperatures and more favorable growing conditions (Luckman, 1994). Similar results were derived from tree-ring analyses of bristlecone pines in the White Mountains of California, where much greater growth was recorded in the eleventh and twelfth centuries (Leavitt, 1994). Analysis of $^{13}C/^{12}C$ ratios in the rings of these trees suggests soil moisture conditions were more favorable in this region during the Medieval Warm Period (Leavitt, 1994). Simultaneous increases in precipitation were found to have occurred in monsoonal locations of the United States desert southwest, where there are indications of increased lake levels from AD 700–1350 (Davis, 1994). Other data document vast glacial retreats during the MWP in parts of South America, Scandinavia, New Zealand, and Alaska (Grove and Switsur, 1994; Villalba, 1994), and ocean-bed cores suggest global sea surface temperatures were warmer then as well (Keigwin, 1996a, 1996b).

The Arctic ice pack substantially retreated during the MWP, allowing the settlement of both Iceland and Greenland, and alpine passes normally blocked with snow and ice became traversable, opening trade routes between Italy and Germany (Crowley and North, 1991). On the northern Colorado Plateau in America, the Anasazi Indian civilization reached its climax as warmer temperatures and better soil moisture conditions allowed them to farm a region twice as large as is currently possible (MacCracken *et al*., 1990).

Huang and Pollack (1997) searched the large database of terrestrial heat flow measurements compiled by the International Heat Flow Commission of the International Association of Seismology and Physics of the Earth's Interior for measurements suitable for reconstructing an average ground surface temperature history of the planet over the past 20,000 years. Working with a total of 6,144 qualifying sets of heat flow data obtained from every continent, they produced a global climate reconstruction independent of other proxy interpretations and of any preconceptions or biases as to the nature of the actual climate history. In this reconstruction of what they called "a global climate history from worldwide observations," the two researchers found strong evidence the MWP was indeed warmer than it had been during any prior portion of the twentieth century, by as much as 0.5°C.

Bard *et al*. (2000) describe some of the many different types of information used to reconstruct past solar variability, including "the envelope of the SSN [sunspot number] 11-year cycle (Reid, 1991), the length and decay rate of the solar cycle (Hoyt and Schatten, 1993), the structure and decay rate of individual sunspots (Hoyt and Schatten, 1993), the mean level of SSN (Hoyt and Schatten, 1993; Zhang *et al*., 1994; Reid, 1997), the solar rotation and the solar diameter (Nesme-Ribes *et al*., 1993), and the geomagnetic aa index (Cliver *et al*., 1998)." They note, "Lean *et al*. (1995) proposed that the irradiance record could be divided into 2 superimposed components: an 11-year cycle based on the parameterization of sunspot darkening and facular brightening (Lean *et al*., 1992), and a slowly-varying background derived separately from studies of Sun-like stars (Baliunas and Jastrow, 1990)."

In their own paper, Bard *et al*. take a different approach. Rather than directly characterizing some aspect of solar variability, certain consequences of that variability are assessed. They note magnetic fields of the solar wind deflect portions of the primary flux of charged cosmic particles in the vicinity of Earth, leading to reductions in the creation of cosmogenic nuclides in Earth's atmosphere, with the result that histories of the atmospheric concentrations of ^{14}C and ^{10}Be can be used as proxies for solar activity, as noted many years previously by Lal and Peters (1967).

Bard *et al*. first created a 1,200-year history of cosmonuclide production in Earth's atmosphere from ^{10}Be measurements of South Pole ice (Raisbeck *et al*., 1990) and the atmospheric $^{14}C/^{12}C$ record as measured in tree rings (Bard *et al*., 1997). This record was then converted to Total Solar Irradiance (TSI) values by "applying a linear scaling using the TSI values published previously for the Maunder Minimum," when cosmonuclide production was 30 to 50 percent above the modern value. The end result of this approach was an extended TSI record suggesting "solar output was significantly reduced between 1450 and 1850 AD, but slightly higher or similar to the present value during a period centered around 1200 AD." They conclude "it could thus be argued that irradiance variations may have contributed to the so-called 'little ice age' and 'medieval warm period.'"

Also noting "the most direct mechanism for climate change would be a decrease or increase in the total amount of radiant energy reaching the Earth," Perry and Hsu (2000) developed a simple solar-luminosity model and used it to estimate total solar-output variations over the past 40,000 years. The model was derived by summing the amplitude of solar radiation variance for fundamental harmonics of the 11-year sunspot cycle throughout an entire 90,000-year glacial cycle, after which the model output was compared with geophysical, archaeological, and historical evidence of climate variation during the Holocene.

They determined model output was well correlated with the amount of carbon 14 (which is produced in the atmosphere by cosmic rays that are less abundant when the Sun is active and more abundant when it is less active) in well-dated tree rings going back to the time of the Medieval Warm Period (about AD 1100). This finding, they write, "supports the hypothesis that the Sun is varying its energy production in a manner that is consistent with the superposition of harmonic cycles of solar activity." The model output also was well correlated with the sea-level curve developed by Ters (1987). Present in both of these records over the entire expanse of the Holocene is a "little ice age"/"little warm period" cycle with a period of approximately 1,300 years. In addition, the climate changes implied by these records correlate well with major historical events. Specifically, the researchers note, "great civilizations appear to have prospered when the solar-output model shows an increase in the Sun's output," and such civilizations "appear to have declined when the modeled solar output declined."

Perry and Hsu note, "current global warming commonly is attributed to increased CO_2 concentrations in the atmosphere," but "geophysical, archaeological, and historical evidence is consistent with warming and cooling periods during the

Holocene as indicated by the solar-output model." They conclude the idea of "the modern temperature increase being caused solely by an increase in CO_2 concentrations appears questionable."

Bond *et al*. (2001) consider what was responsible for the approximate 1,500-year cycle of global climate change in the North Atlantic Ocean that had been intensely studied and demonstrated to prevail throughout both glacial and interglacial periods alike. They studied ice-rafted debris found in three North Atlantic deep-sea sediment cores and cosmogenic nuclides sequestered in the Greenland ice cap (^{10}Be) and Northern Hemispheric tree rings (^{14}C).

Based on analyses of the deep-sea sediment cores that yielded the variable-with-depth amounts of three proven proxies for the prior presence of overlying drift-ice, the scientists were able to discern and (using an accelerator mass spectrometer) date a number of recurring alternate periods of relative cold and warmth in the 12,000-year expanse of the Holocene. They determined the mean duration of the several complete climatic cycles was 1,340 years, and the cold and warm nodes of the most recent of these oscillations were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period.'"

The ten scientists linked these millennial-scale climate oscillations and their embedded centennial-scale oscillations with similar-scale oscillations in cosmogenic nuclide production, which are known to be driven by oscillations in the energy output of the Sun. Bond *et al*. report, "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum." They conclude, "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the variable solar inferno are experienced throughout the world.

The international team of scientists verified that in spite of the contrary claims, the Little Ice Age and Medieval Warm Period were real, global, solar-induced, and but the latest examples of alternating intervals of relative cold and warmth stretching back in time through glacial and interglacial periods alike. Because these subjects are of such great significance to the debate over climate model-predicted consequences of anthropogenic CO_2 emissions, Bond *et al.* cite additional evidence in support of the implications of their work.

With respect to the global extent of the climatic impact of the solar radiation variations they detected, they make explicit reference to confirmatory studies conducted in Scandinavia, Greenland, the Netherlands, the Faroe Islands, Oman, the Sargasso Sea, coastal West Africa, the Cariaco Basin, equatorial East Africa, and the Yucatan Peninsula, demonstrating the footprint of the solar impact on climate they documented extends "from polar to tropical latitudes." They also note "the solar-climate links implied by our record are so dominant over the last 12,000 years ... it seems almost certain that the well-documented connection between the Maunder solar minimum and the coldest decades of the Little Ice Age could not have been a coincidence." They further note their findings support previous suggestions that both the Little Ice Age and Medieval Warm Period "may have been partly or entirely linked to changes in solar irradiance."

Bond *et al*. reiterate that the oscillations in drift-ice "persist across the glacial termination and well into the last glaciation, suggesting that the cycle is a pervasive feature of the climate system." At two of their coring sites, they identified a series of cyclical variations that extended throughout all of the previous interglacials and were "strikingly similar to those of the Holocene." Here, they also could have cited the work of Oppo *et al*. (1998), who observed similar climatic oscillations in a sediment core that covered the period from 340,000 to 500,000 years before present, and of Raymo *et al*. (1998), who pushed back the time of the cycles' earliest known occurrence to well over one million years ago.

With respect to how the small changes in solar radiation inferred from cosmogenic nuclide variations bring about such significant and pervasive shifts in Earth's global climate, a question that had long plagued proponents of a solar-climate link, Bond *et al*. describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth's surface, where they likely provoke changes in North Atlantic deep water formation that alter the global thermohaline circulation. They suggest the solar signals "may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint."

Concluding their landmark paper, the ten scientists state the results of their study "demonstrate that the Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output," noting their work "supports the presumption that solar variability will continue to influence climate in the future."

Rigozo *et al*. (2001) reconstructed a history of sunspot numbers for the past 1,000 years "using a sum of sine waves derived from spectral analysis of the time series of sunspot number R_Z for the period 1700–1999," and from that record derived the strengths of a number of parameters related to solar variability over the past millennium.

The four researchers state, "the 1,000-year reconstructed sunspot number reproduces well the great maximums and minimums in solar activity that are identified in cosmonuclide variation records, and, more specifically, in the epochs of the Oort, Wolf, Sporer, Maunder, and Dalton Minimums, as well as the Medieval and Modern Maximums," the latter of which they describe as "starting near 1900." They report the mean sunspot number for the Wolf, Sporer, and Maunder Minimums was 1.36; for the Oort and Dalton Minimums it was 25.05; for the Medieval Maximum it was 53.00; and for the Modern Maximum it was 57.54. The mean sunspot number of the Oort and Dalton Minimums was thus 18.42 times greater than the average of the Wolf, Sporer, and Maunder Minimums, while the mean sunspot number of the Medieval Maximum was 38.97 times greater and the Modern Maximum 42.31 times greater. Similar strength ratios for the solar radio flux were 1.41, 1.89, and 1.97, respectively, and for the solar wind velocity the corresponding ratios were 1.05, 1.10, and 1.11, while for the southward component of the interplanetary magnetic field they were 1.70, 2.54, and 2.67.

Clearly, the sunspot number and solar variability paramenters of the Medieval and Modern Maxima are dramatically greater than all other periods of the past thousand years. Thus, for entirely natural reasons, future temperatures may be higher than at any other time during the past millennium. Of course, other natural factors also affect Earth's climate system and may mitigate that conclusion. In any event, the observations of Rigozo *et al*. and those of Bond *et al*. suggest there is no need for invoking variations in the air's CO_2 content as the primary cause of mean global temperature variations during any period of the past thousand or more years.

Esper *et al*. (2002) employed a technique that allows accurate long-term climatic trends to be derived from individual tree-ring series of much shorter duration than the potential climatic oscillation being studied, and they applied this technique to more than 1,200 tree-ring series derived from 14 locations over the extratropical region of the Northern Hemisphere.

Two chronologies were thus developed: one from trees that exhibited weakly linear age trends and one from trees with nonlinear age trends. The results, they write, were "two nearly independent tree-ring chronologies covering the years 800–1990," which were "very similar over the past ~1200 years." These tree-ring histories were calibrated against Northern Hemispheric (0 to 90°N) mean annual instrumental temperatures from the period 1856–1980 to make them compatible with the temperature reconstructions of Mann *et al*. (1998, 1999), which were being cited by the IPCC and others as evidence current temperatures were greater than any previously experienced over the prior thousand years.

The biggest difference between the Esper *et al*. and Mann *et al*. temperature histories was the degree to which the coolness of the global Little Ice Age was expressed. It was much more evident in the record of Esper *et al*., and its significantly lower temperatures made the Medieval Warm Period stand out more dramatically in their temperature reconstruction. Also, they note, "the warmest period covers the interval 950–1045, with the peak occurring around 990." This finding, they write, "suggests that past comparisons of the Medieval Warm Period with the 20th-century warming back to the year 1000 have not included all of the Medieval Warm Period and, perhaps, not even its warmest interval."

In a companion "perspective" paper, Briffa and Osborn (2002) acknowledge "the last millennium was much cooler than previously interpreted" and "an early period of warmth in the late 10th and early 11th centuries is more pronounced than in previous large-scale reconstructions." The Esper *et al*. record makes it abundantly clear the peak warmth of the MWP was equivalent to the warmth of the late twentieth and early twenty-first centuries.

This reaffirms the point raised by Idso (1988): that there is no need to invoke CO_2-induced global warming as a cause of the planet's recovery from the global chill of the Little Ice Age. "Since something other than atmospheric CO_2 variability was ... clearly responsible for bringing the planet into the Little Ice Age," he writes, "something other than atmospheric CO_2 variability may just as well have brought the planet out of it." That something else, as suggested by Esper *et al*., was probably "the 1000- to 2000-year climate rhythm (1470 ± 500 years) in the North Atlantic, which may be related to solar-forced changes in thermohaline circulation," as had been described by Bond *et al*. (2001).

Briffa and Osborn also note Esper *et al*.'s record clearly shows the warming of the twentieth century was simply "a continuation of a trend that began at the start of the 19th century." In addition, the Esper *et al*. record indicates the Northern Hemisphere warmed in a consistent near-linear fashion over this 200-year period, contrary to the IPCC's claim of unprecedented warming over only the last century. The new data did great damage to the assertion CO_2-enhanced greenhouse warming was responsible for the temperature increase that brought the planet out of the Little Ice Age, since the increase in the air's CO_2 concentration over this period was highly nonlinear, rising by only 10 to 15 ppm over the nineteenth century but fully 70 to 75 ppm over the twentieth century, with no analogous increase in the latter period's rate of warming.

Briffa and Osborn also state, "we need to know why it was once so warm and then so cool, before we can say whether 21st-century warming is likely to be nearer to the top or the bottom of the latest IPCC [predicted temperature] range." We probably already know the answer to that question: The extremes of warmth and coolness to which they refer likely were caused by "solar-forced changes in thermohaline circulation," as suggested by Esper *et al*. and described by Bond *et al*.

Krenke and Chernavskaya (2002) review the then-current state of knowledge about the Medieval Warm Period and Little Ice Age, throughout the world in general and in Russia in particular, based on written historical, glaciological, and hydrologic evidence and dendrological, archaeological, and palynological data. "Concerning the Medieval Warm Period (MWP)," they write, "it is currently known that, from the 9th century to, apparently, the mid-15th century, the climatic conditions were warmer than during most of the subsequent five centuries, including the early 20th century." In some places it was warmer during the MWP than during the latter part of the twentieth century. For example, they note "the northern margin of boreal forests in Canada was shifted by 55 km [north] during the MWP, and the tree line in the Rocky Mountains in the southern United States and in the Krkonose Mountains was higher by 100–200 m than that observed at the present time."

Regarding the temperature reconstructions of Mann *et al*. (1998, 1999), the two members of the Russian Academy of Sciences state "the temperature averaged over the 20th century was found to be the highest among all centennial means, although it remained within the errors of reconstructions for the early millennium." They further note, "one should keep in mind that the reconstructions of the early period were based nearly entirely on tree-ring data, which, because of the features of their interpretation, tend to underestimate low-frequency variations, so the temperatures of the Medieval Warm Period were possibly underestimated." They provide further evidence for that conclusion, reporting, "the limits of cultivated land or receding glaciers have not yet exceeded the level characteristic of the early millennium."

Specifically with respect to Russia, Krenke and Chernavskaya report large differences in several variables between the period of the Little Ice Age and the preceding Medieval Warm Period. With respect to the annual mean temperature of northern Eurasia, they report an MWP to LIA drop of 1.5°C. They also state, "the frequency of severe winters reported was increased from once in 33 years in the early period of time, which corresponds to the MWP, to once in 20 years in the LIA," and they note "the abnormally severe winters [of the LIA] were associated with the spread of Arctic air masses over the entire Russian Plain." Finally, they note the data they used to draw these conclusions were "not used in the reconstructions performed by Mann *et al*.," which may explain why the Mann *et al*. temperature history of the past millennium does not reproduce the Little Ice Age nearly as well as does the more appropriately derived temperature history of Esper *et al*. (2002).

In contradiction of another of Mann *et al*.'s contentions, Krenke and Chernavskaya unequivocally state, based on the results of their study of the relevant scientific literature, "the Medieval Warm Period and the Little Ice Age existed globally."

Soon and Baliunas (2003) also reviewed evidence pertaining to the climatic and environmental history of Earth over the past millennium. They found "the assemblage of local representations of climate establishes both the Little Ice Age and Medieval Warm Period as climatic anomalies with worldwide imprints, extending earlier results by Bryson *et al*. (1963), Lamb (1965), and numerous intervening research efforts." In addition, they write, "across the world, many records reveal that the 20th century is probably not the warmest nor a uniquely extreme climatic period of the last millennium."

Mayewski *et al*. (2004) examined 50 globally distributed paleoclimate records in search of evidence for what they called *rapid climate change* (RCC) over the Holocene. This terminology is not to be confused with the rapid climate changes typical of glacial periods, but is used in the place of what the 16 researchers call the "more geographically or temporally restrictive terminology such as 'Little Ice Age' and 'Medieval Warm Period.'" RCC events, as they also refer to them, are multi-century periods characterized by extremes of thermal and/or hydrological properties, rather than the much shorter periods when the changes that led to these situations took place.

Mayewski *et al*. say they identified six RCCs during the Holocene: 9,000–8000, 6,000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 cal yr BP, the last two of which are the "globally distributed" Medieval Warm Period and Little Ice Age, respectively. They note, "the short-lived 1200–1000 cal yr BP RCC event coincided with the drought-related collapse of Maya civilization and was accompanied by a loss of several million lives (Hodell *et al*., 2001; Gill, 2000), while the collapse of Greenland's Norse colonies at ~600 cal yr BP (Buckland *et al*., 1995) coincides with a period of polar cooling."

With respect to the causes of these and other Holocene RCCs, the international team of scientists concludes, "of all the potential climate forcing mechanisms, solar variability superimposed on long-term changes in insolation (Bond *et al*., 2001; Denton and Karlen, 1973; Mayewski *et al*., 1997; O'Brien *et al*., 1995) seems to be the most likely important forcing mechanism." They also declare "negligible forcing roles are played by CH_4 and CO_2," and "changes in the concentrations of CO_2 and CH_4 appear to have been more the result than the cause of the RCCs."

Braun *et al*. (2005) note many palaeoclimate records from Earth's North Atlantic region depict a millennial-scale oscillation of climate, which during the last glacial period was highlighted by Dansgaard-Oeschger events that regularly recurred at approximately 1,470-year intervals, as reported by Rahmstorf (2003). Because of the consistency of their occurrence, it was generally believed these well-tuned periodic events were orchestrated by similarly paced solar activity, but no known solar process or orbital perturbation exhibited the periodicity of the Dansgaard-Oeschger events. Braun *et al*. (2005) performed an analysis that successfully explains this dichotomy.

Noting the periods of the DeVries-Suess and Gleissberg solar cycles (~210 and 87 years, respectively) are close to prime factors of 1,470 years, the team of eight German scientists write, "the superposition of two such frequencies could result in variability that repeats with a 1,470-year period." They proceed to show "an intermediate-complexity climate model with glacial climate conditions simulates rapid climate shifts similar to the Dansgaard-Oeschger events with a spacing of 1,470 years when forced by periodic freshwater input into the North Atlantic Ocean in cycles of ~86 and ~210 years." The researchers state this exercise is "not aimed at suggesting a certain mechanism for solar influence on freshwater fluxes," as they describe it, but merely to demonstrate "the glacial 1,470-year climate cycles could have been triggered by solar forcing despite the absence of a 1,470-year solar cycle."

Braun *et al*.'s work suggests the similarly paced millennial-scale oscillation of climate that has reverberated throughout the Holocene, but with less perfect regularity, also is driven by the combined effect of the DeVries-Suess and Gleissberg solar cycles. The German scientists state the stimulus for their idea that "a multi-century climate cycle might be linked with century-scale solar variability comes from Holocene data," citing the work of Bond *et al*. (2001), who had found "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum," and who concluded, "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic."

Bond *et al*. report the climatic oscillation's most recent cold node and the warm node that preceded it were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period.'" Similarly, Rahmstorf states "the so-called 'little ice age' of the 16th–18th century may be the most recent cold phase of this cycle." The logical extension of these observations is that the global warming of the past century or so, which propelled Earth out of the Little Ice Age and into the Current Warm Period, was a result of the most recent upswing in this continuing cycle of solar-induced climate change rather than any increase in the atmosphere's CO_2 concentration.

Esper *et al*. (2005) sought to explain the significant differences among climatic reconstructions and what might be necessary to reduce uncertainties in order to gain a more complete and correct understanding of temperature changes over the past thousand years. According to the six scientists, for the most part we understand the *shape* of long-term climate fluctuations better than their *amplitudes*. For example, nearly all 1,000-year temperature reconstructions capture the major climatic episodes of the Medieval Warm Period, Little Ice Age, and Current Warm Period, but they exhibit differences in the degree of warming or cooling identified in the transitions between them, which for decadal means may amount to as much as 0.4 to 1.0°C.

Esper *et al.* suggest these discrepancies might be addressed by reducing the calibration uncertainty among the proxies, ensuring the accurate preservation and assessment of low-to-high frequency variation in proxy data, using appropriate frequency bands to best fit instrumental data, avoiding the use of regional tree-ring and other paleo-records in which long-term trends (low-frequency variations) are not preserved, selecting instrumental data with which to compare proxy records to avoid incorrect alterations to the observational data that can result from homogeneity adjustments and methodological differences, and obtaining more proxy data that cover the full millennium and represent the same spatial domain as the instrumental target data.

Esper *et al*. note knowledge of the correct amplitude of the major climatic episodes of the past millennium is "critical for predicting future trends." If the amplitudes of the major historical climate episodes were as large as, or even greater than, the twentieth century global warming, there would be what they describe as a "redistribution of weight towards the role of natural factors in forcing temperature changes, thereby relatively devaluing the impact of anthropogenic emissions and affecting future predicted scenarios." Efforts to reduce greenhouse gas emissions via national or international agreements "would be less effective than thought."

Using data from 18 non-tree-ring-based 2,000-year proxy temperature series from around the world, Loehle (2007) smoothed the data in each series with a 30-year running mean, converted the results to anomalies by subtracting the mean of each series from each member of that series, and derived the final mean temperature anomaly history defined by the datasets by a simple averaging of the individual anomaly series. The results depict the Medieval Warm Period and Little Ice Age quite clearly, with the peak warmth of the MWP showing as approximately 0.3°C warmer than the peak warmth of the twentieth century. In a subsequent paper, Loehle and McCulloch (2008) obtained the results depicted in Figure 4.2.2.4. Although instrumental data are not strictly comparable to the reconstructed proxy data, the rise in global data from NASA GISS from 1935 (the end point of the figure) to 1992 (with data from 1978 to 2006) is 0.34°C, and "adding this rise to the 1935 reconstructed value, the MWP peak still remains 0.07°C above the end of the 20th-century values, though the difference is not significant."

Based on data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland and using regional curve standardization (RCS) procedures, Helama *et al*. (2009) developed "the first European dendroclimatic precipitation reconstruction," which "covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP)," running from AD 670 to AD 1993. These data indicate "the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD," which "precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture." In addition, they write, "the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930)."

The three Finnish scientists note "the global medieval drought that we found occurred in striking temporal synchrony with the multi-centennial droughts previously described for North America (Stine, 1994; Cook *et al*., 2004, 2007), eastern South America (Stine, 1994; Rein *et al*., 2004), and equatorial East Africa (Verschuren *et al*., 2000; Russell and Johnson, 2005, 2007; Stager *et al*., 2005) between AD 900 and 1300." Noting further "the global evidence argues for a common force behind the hydrological component of the MCA," they report "previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren *et al*., 2000; Stager *et al*., 2005) or the ENSO (Cook *et al*., 2004, 2007; Rein *et al*., 2004; Herweijer *et al*., 2006, 2007; Graham *et al*., 2007, Seager *et al*., 2007)." They conclude, "the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the $\Delta^{14}C$ and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki *et al*., 2004)."

Esper and Frank (2009) took the IPCC to task for concluding in its *Fourth Assessment Report* (AR4) that, relative to modern times, there was "an increased heterogeneity of climate during medieval times about 1000 years ago." This finding, if true, would be of

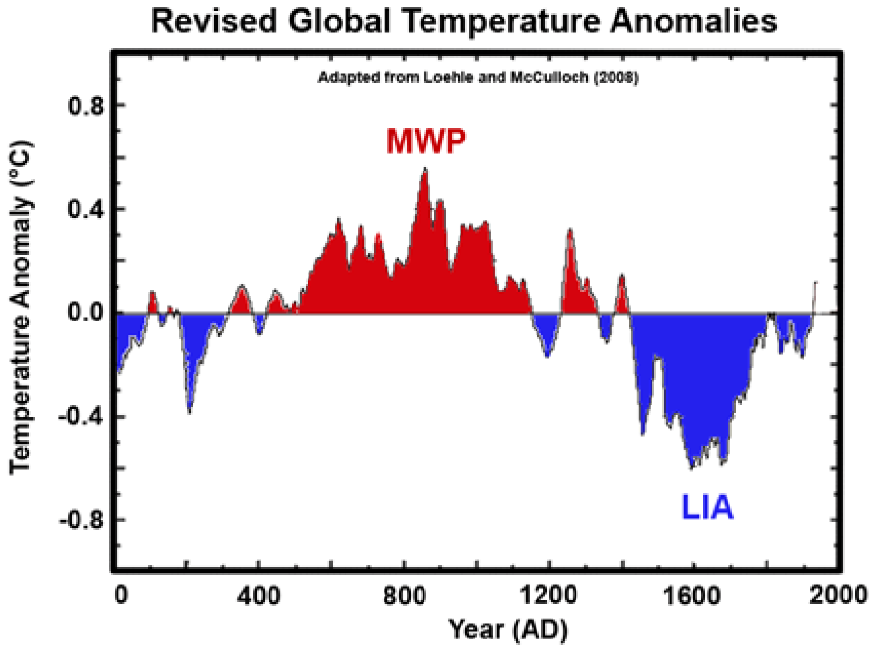

Figure 4.2.2.4. Mean relative temperature history of the globe. Adapted from Loehle, C. and McCulloch, J.H. 2008. Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment* **19**: 93–100.

great significance to the ongoing debate over the cause of twentieth century global warming because, as Esper and Frank note, "heterogeneity alone is often used as a distinguishing attribute to contrast with present anthropogenic warming." But if the IPCC's contention is false, it would mean the warmth of the Current Warm Period is not materially different from that of the Medieval Warm Period, suggesting there is no need to invoke anthropogenic CO_2 emissions as the cause of Earth's current warmth.

With mathematical procedures and statistical tests, Esper and Frank demonstrate the records reproduced in the AR4 "do not exhibit systematic changes in coherence, and thus cannot be used as evidence for long-term homogeneity changes." They also note "there is no increased spread of values during the MWP," and the standard error of the component datasets "is actually largest during recent decades." Consequently, the two researchers conclude their "quantification of proxy data coherence suggests that it was erroneous [for the IPCC] to conclude the records displayed in AR4 are indicative of a heterogeneous climate during the MWP."

The studies cited in this section clearly establish the verity of a global Medieval Warm Period. Hundreds of additional papers are cited in Sections 4.2.3 and 4.2.4.

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4.2.3 Prior Warm Periods in the Northern Hemisphere

Citing the work of Mann *et al*. (1998, 1999), the IPCC concluded in its *Fourth Assessment Report* that late twentieth century warming was unprecedented over the past millennium, a conclusion that remains intact in the IPCC's most recent report:

> For average annual Northern Hemisphere temperatures, there is *medium confidence* that 1981–2010 CE was the warmest 30-year period of the last 1300 years and it is *very likely* that it was the warmest of the last 800 years (Second Order Draft of AR5, dated October 5, 2012, p 5–4)

As shown in this subsection, the IPCC is clearly ignoring the findings of several research teams who have presented results that counter their claims.

The Medieval Warm Period and subsequent Little Ice Age, which followed the Roman Warm Period and the Dark Ages Cold Period (McDermott *et al*., 2001), were long considered classic examples of the warm and cold phases of a millennial-scale climate oscillation that has reverberated throughout glacial and interglacial periods (Oppo *et al*., 1998; McManus *et al*., 1999) as well as across the early Pleistocene (Raymo *et al*., 1998).

In addition to their intrinsic historical value, the last of these alternating warm and cold periods are of particular relevance to the global warming debate. If there truly was a period near the beginning of the past millennium when temperatures were as warm as they are presently, but when the atmosphere's CO_2 concentration was only about 40 percent of today's level (280 ppm vs. 400 ppm), and if that period was followed by a several-centuries-long cold period with essentially no decline in the air's CO_2 content, there would be little basis for invoking the twentieth century increase in atmospheric CO_2 concentration as a reason for the planet's return to the warmth it had experienced a millennium earlier, as Idso (1988) argued a quarter-century ago and Broecker (1999) noted a decade later.

A pair of papers published by Mann *et al*. (1998, 1999) near the turn of the twenty-first century presented an interpretation of Earth's climatic history vastly different from what previously had been accepted by even the IPCC (Houghton *et al*., 1990), which up to at least 1995 had depicted the existence of both the Medieval Warm Period and the Little Ice Age. The new history, derived from select proxy temperature records, showed, in the words of Esper *et al*. (2002), "an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time," which is now routinely described by the IPCC as "the warmest period of the past millennium." A few years later, the work of Esper *et al*. (2002) reaffirmed the earlier understanding of these unique climatic periods.

Esper *et al*. employed an analysis technique that allowed long-term climate trends to be derived from individual tree-ring series of much shorter duration than the potential climatic oscillation being studied, and they applied this technique to more than 1,200 tree-ring series derived from 14 locations over the extratropical region of the Northern Hemisphere. Two separate chronologies were developed: one from trees that exhibited weakly linear age trends and one from trees with nonlinear age trends. The outcome, they write, was "two nearly independent tree-ring chronologies covering the years 800–1990," which were "very similar over the past ~1200 years." These tree-ring histories were calibrated against Northern Hemispheric (0 to 90°N) mean annual instrumental temperatures from the period 1856–1980 to make them compatible with the temperature reconstructions of Mann *et al*.

The biggest difference between the Esper *et al*. and Mann *et al*. temperature histories is the degree to which the coolness of the Little Ice Age is expressed. The Little Ice Age is much more evident in the record of Esper *et al*., and its significantly lower temperatures make the Medieval Warm Period stand out more dramatically. Esper *et al*. note, "the warmest period covers the interval 950–1045, with the peak occurring around 990." This finding, they write, "suggests that past comparisons of the Medieval Warm Period with the 20th-century warming back to the year 1000 have not included all of the Medieval Warm Period and, perhaps, not even its warmest interval."

In a companion "perspective" paper, Briffa and Osborn (2002) acknowledge the last millennium "was much cooler than previously interpreted" and "an early period of warmth in the late 10th and early 11th centuries is more pronounced than in previous large-scale reconstructions."

Esper *et al.*'s work reaffirms the point raised by Idso (1988): There is no need to invoke CO_2-induced global warming as a cause of the planet's recovery from the global chill of the Little Ice Age. "Since something other than atmospheric CO_2 variability was ... clearly responsible for bringing the planet into the Little Ice Age," he notes, "something other than atmospheric CO_2 variability may just as well have brought the planet out of it." That something else, as suggested by Esper *et al*., is probably "the 1000- to 2000-year climate rhythm (1470 ± 500 years) in the North Atlantic, which may be related to solar-forced changes in thermohaline circulation" as described by Bond *et al*. (2001).

Briffa and Osborn also note Esper *et al*.'s record clearly shows the warming of the twentieth century was "a continuation of a trend that began at the start of the 19th century." In addition, the Esper *et al*. record indicates the Northern Hemisphere warmed in a consistent near-linear fashion over this 200-year period, contrary to the claim of unprecedented warming over only the last century.

Briffa and Osborn conclude, "we need to know why it was once so warm and then so cool, before we can say whether 21st-century warming is likely to be nearer to the top or the bottom of the latest IPCC [predicted temperature] range." The answer to this question is already known: The extremes of warmth and coolness to which Briffa and Osborn refer were likely caused by "solar-forced changes in thermohaline circulation," as suggested by Esper *et al*. and described by Bond *et al*. It has become increasingly clear these significant climatic changes were not caused by changes in the air's CO_2 content.

Briffa *et al*. (2002) worked with a network of high-latitude and high-elevation tree-ring chronologies obtained from 387 conifer sites that circled the extra-tropical Northern Hemisphere, comprised of almost 10,000 individual tree cores with chronologies ranging in length from 85 to more than 600 years, to reconstruct a "near-hemispheric scale" April-to-September temperature history. Based on the trees' maximum latewood density, this temperature reconstruction exhibits a strong, spatially coherent response to decadal-scale temperature variability, but because of the particular standardization procedure they employed, Briffa *et al*. state their reconstruction was "likely to remove the century to multicentury timescale power." The following discussion is limited to a consideration of what their work implied about the warming of the Northern Hemisphere in only the late twentieth century.

The year of coldest growing-season temperature in Briffa *et al*.'s reconstruction was 1912, after which temperatures rose in zigzag fashion to about 1930, whereupon they flattened out until approximately 1945, after which they declined in zigzag fashion until sometime in the late 1970s, when they began to fluctuate about a well-defined mean that persisted to the end of the century. At the dawning of the new millennium, Briffa *et al*.'s proxy temperatures were considerably below the peak warmth of the 1930s and early 1940s, in striking contrast to the instrumental temperature record, which soared to new heights in the 1980s and 1990s to achieve the century's highest values, which were several tenths of a degree Centigrade greater than the temperatures derived from the 10,000 trees' maximum latewood density data. Mann *et al*. (1998, 1999) used instrumental temperatures in lieu of proxy temperatures over the latter part of the century to arrive at what they called the "unprecedented" warming of its last two decades.

Is it appropriate, as Mann *et al.* did, to "switch horses" and compare two different things—early-century *proxy* temperatures and late-century *instrumental* temperatures—to conclude the twentieth century experienced unprecedented warming over its final two decades? Or is it more appropriate to finish the comparison with the parameter with which you began, which leads to the conclusion that the end of the century was likely no warmer than it was in the 1930s and early 1940s?

Briffa *et al*. approached this predicament by first acknowledging the existence of the problem, which they describe as "a deviation between reconstructed and observed temperature during the most recent three or four decades," noting the deviation increases with time, "particularly since about 1970 (although perhaps starting as early as 1935)." They admit they could not find a "substantiated explanation for it," so they *assumed* the deviation "is likely to be a response to some kind of recent anthropogenic forcing." And they also assumed the anthropogenic forcing had perturbed the *proxy* temperature record.

A much less convoluted course of action would have been to assume the anthropogenic forcing had perturbed the *instrumental* temperature record. There is, after all, a well-known and "substantiated explanation" for this point of view: that Earth's increasing population has been increasing the strength of urban heat island and altered land-use effects nearly everywhere on the land surface of the planet, and sufficiently accurate adjustments to the instrumental temperature record for these phenomena had not yet been made throughout the regions investigated by Briffa *et al*.

Since 1970, for example, the world's population had grown by approximately 64 percent, and since 1935, when the first signs of the deviation between the proxy and instrumental temperature records began to occur, the number of people on the planet had grown by more than 200 percent. With urban heat islands routinely raising city air temperatures several degrees Centigrade above the temperatures of their surrounding rural environs, and since towns with as few as a thousand inhabitants have been shown to possess heat islands of two degrees Centigrade or more (Oke, 1973; Torok *et al*., 2001), it is clear population growth easily could have produced a gradually increasing elevation of the instrumental temperature record (typically developed from temperatures measured in cities and towns) relative to the basically rural temperature record typical of the locations where the tree-ring chronologies studied by Briffa *et al*. were obtained. This phenomenon easily could account for the several tenths of a degree Centigrade by which instrumental and proxy temperature records differed at the end of the twentieth century.

There are several other reasons for accepting this analysis of the diverging-temperature-records dilemma instead of yielding to the six scientists' default assumption. Briffa *et al.* could identify no credible mechanism for producing the problem they imagined to exist with the late twentieth century proxy temperatures, so they gave up, saying "to search for an explanation is beyond the scope of this paper." They could not produce an explanation that would apply to the entire Northern Hemisphere and be readily comprehended by most reasonable people as having at least the potential to be correct.

One also wonders what kind of "recent anthropogenic forcing" could have had such a substantial negative effect on tree growth and wood density over the latter part of the twentieth century. Atmospheric pollution is one possibility, especially rising ozone (O_3) concentrations. However, in numerous studies of the net effect of elevated O_3 and CO_2 acting together on trees, the positive effects of elevated CO_2 often have been found to compensate, and sometimes even more than compensate, for the negative effects of elevated O_3 (Grams *et al*., 1999; Noormets *et al*., 2001; Liu *et al*., 2004). The positive effects of elevated CO_2 also have been found to compensate for the negative effects of elevated sulfur dioxide concentrations (Deepak and Agrawal, 2001; Izrael *et al*. (2002); Agrawal and Deepak, 2003). Rising atmospheric CO_2 concentrations are known to significantly stimulate the growth rates of essentially all woody plants and increase the density of the wood produced by trees (Kilpelainen *et al*., 2003; Kostiainen *et al*., 2004).

In light of these observations, it is highly unlikely human activity is reducing the growth and wood density of Earth's trees, especially those growing in the relatively remote locations used to develop the data analyzed by Briffa *et al*. It is far more likely the divergence of the instrumental and proxy temperature records analyzed by Briffa *et al*. is caused by an anthropogenic effect on the *instrumental* record than on proxy record. Thus the hockey stick temperature record of Mann *et al*. (1998, 1999) would appear to be patently erroneous over the last few decades of the twentieth century, substituting as it does the increasingly inflated instrumental temperature record for the more correct and stable proxy temperature record.

Esper and a group of five new coauthors—Esper *et al*. (2003)—processed several long juniper tree-ring-width chronologies for the Alai Range of the western Tien Shan in Kirghizia in way that preserved multi-centennial growth trends typically "lost during the processes of tree ring data standardization and chronology building (Cook and Kairiukstis, 1990; Fritts, 1976)." They used two techniques that maintain low frequency signals—long-term mean standardization (LTM) and regional curve standardization (RCS)—as well as the more conventional spline standardization (SPL) technique that obscures (actually removes) such long-term trends.

Carried back in time a full thousand years, the SPL chronologies depicted significant interdecadal variations but no longer-term trends. The LTM and RCS chronologies, by contrast, showed long-term decreasing trends until about AD 1600, broad minima from 1600 to 1800, and long-term increasing trends from about 1800. Esper *et al*. write, "the main feature of the LTM and RCS Alai Range chronologies is a multi-centennial wave with high values towards both ends."

This result has essentially the same form as the Northern Hemispheric extratropic temperature history of Esper *et al*. (2002), which is vastly different from the hockey stick temperature history of Mann *et al*. (1998, 1999) and Mann and Jones (2003), in that it depicts the existence of both the Little Ice Age and the preceding Medieval Warm Period, which are nowhere to be found in the Mann reconstructions. The new result—especially the LTM chronology, which has a much smaller variance than the RCS chronology—depicts several periods in the first half of the past millennium that were warmer than any part of the past century. These periods include much of the latter half of the Medieval Warm Period and a good part of the first half of the fifteenth century, which also has been found to have been warmer than it is currently (McIntyre and McKitrick, 2003; Loehle, 2004).

Briffa *et al*. (2004) reviewed several analyses of maximum latewood density data derived from a widespread network of tree-ring chronologies that spanned three to six centuries and were obtained from nearly 400 different locations. For the land area of the globe poleward of 20°N latitude, their work reveals the warmest period of the past six centuries occurred in the 1930s and early 1940s. Thereafter, the mean temperature of the region declined dramatically. It recovered somewhat over the last two decades of the twentieth century, but its final value was still below the mean value of the 1400s and portions of the 1500s.

Averaged over all land area poleward of 50°N latitude, there was a marked divergence of reconstructed and instrumental temperatures subsequent to 1960, with measured temperatures rising and reconstructed temperatures falling, such that by the end of the record there was an approximate 1.5°C difference between them. The three researchers attempted to relate this large temperature differential to a hypothesized decrease in tree growth caused by a hypothesized increase in ultraviolet radiation, which they hypothesized to have been caused by declining stratospheric ozone concentrations over this period. The results of this effort, however, proved "equivocal," as they describe them, leaving considerable room for urban heat island effects and other land-cover changes to have been the principal causes of the observed temperature divergence, as suggested by Gallo *et al*. (1996, 1999) and Kalnay and Cai (2003). Briffa *et al.* state these unsettled questions prevented them "from claiming unprecedented hemispheric warming during recent decades on the basis of these tree-ring density data alone." Their analyses also fail to provide convincing evidence for the validity of the Northern Hemispheric temperature reconstructions of Mann *et al*. (1998, 1999) and thus fail to support the IPCC's contention that the warming of high northern latitudes should be significantly greater than that of the rest of the Northern Hemisphere.

While studying lichens of the subspecies *Rhizocarpon geographicum* found on avalanche boulder tongues in the eastern part of the Massif des Ecrins of the French Alps, Jomelli and Pech (2004) made an important discovery: High-altitude avalanche activity during the Little Ice Age reached an early maximum prior to 1650, after which it decreased until about 1730, whereupon it increased once again, reaching what was likely its greatest maximum about 1830. The two researchers note "a greater quantity of snow mobilized by avalanches during the LIA can be supported by the fact that the two periods, AD 1600–1650 and 1830, during which the run-out distances [of the avalanches] were maximum at high elevation sites, have corresponded overall to the periods of maximum glacial advances for these last 500 years (Le Roy Ladurie, 1983; Reynaud, 2001)." In addition, they report "since 1850 most French Alpine glaciers have decreased" and "the mass balance of these glaciers is directly correlated with summer temperature and spring precipitation (Vincent and Vallon, 1997; Vincent, 2001, 2002)."

These findings and those of other scientists cited by Jomelli and Pech suggest the beginning of the end of the Little Ice Age started somewhere in the early to mid-1800s. Moore *et al*. (2002) determined a similar start-time for the demise of the Little Ice Age from temperature data gathered on Mount Logan in Canada, and further support for this conclusion has come from studies of still other parameters, including deep soil temperatures (Gonzalez-Rouco *et al*., 2003), deep ocean temperatures (Lindzen, 2002), and dates of ice break-up of lakes and rivers (Yoo and D'Odorico, 2002). This is also when the temperature record of Esper *et al*. (2002) indicates the Northern Hemisphere began its nearly-linear-with-time recovery from the depths of the Little Ice Age. As Briffa and Osborn (2002) describe it, Esper *et al*.'s record clearly shows the warming of the twentieth century was actually "a continuation of a trend that began at the start of the 19th century."

The temperature history of Mann *et al*. (1998, 1999) suggests post-Little Ice Age warming did not begin until about 1910. They appear to have missed as much as half the warming experienced by Earth in recovering from what was likely the coldest part of the Little Ice Age. An even greater part of the total warming occurred before the air's CO_2 concentration began increasing in earnest (approximately 1930, close to the time when warming peaked in the United States and many other parts of the world). Thus the lion's share of the warming of the past nearly two centuries must owe its existence to something other than rising atmospheric CO_2 concentrations.

Gray *et al*. (2004) write, "natural, low-frequency variations" in near-surface air temperature may "mask or amplify secular trends in the climate system." Hence, it is important—even necessary—to study such phenomena in order to determine the cause or causes of recent climate change. Gray *et al*. developed a reconstruction of the leading mode of low-frequency North Atlantic (0–70°N) sea surface temperature variability—i.e., the Atlantic Multidecadal Oscillation (AMO)—for the period AD 1567–1990, based on tree-ring records from regions known to border on strong centers of AMO variability: eastern North America, Europe, Scandinavia, and the Middle East.

In terms of both duration and magnitude, the four researchers found the "AMO variability observed in late-19th and 20th century instrumental records is typical of North Atlantic multidecadal behavior over longer periods." They also observed a new warming phase had begun in the mid-1990s and the most intense warm phase of the AMO record occurred between 1580 and 1596.

Gray *et al*. say the first of these findings suggests "the mechanisms driving AMO variability have operated in a similar fashion for (at least) the previous 500 years," and "trace-gas forcing has yet to significantly affect the low-frequency component of THC [thermohaline circulation] variability." Their work also suggests trace-gas forcing has yet to significantly affect the near-surface air temperature of the Northern Hemisphere, and the identification of the start of a new warming phase in the mid-1990s suggests the supposedly record temperatures of the past decade or so may have been driven more by natural AMO variability than increasing greenhouse gas concentrations.

The most intense warm phase of the AMO record of Gray *et al*. occurred near the end of the time frame associated with evidence of what could be called the "Little" Medieval Warm Period, when global air temperature may have been significantly warmer than it has been at any subsequent time, clearly evident in Gray *et al*.'s reconstruction of North Atlantic SST anomalies. Thus the evidence continues to mount for the existence of a warm period in the general vicinity of the 1500s, when the air's CO_2 content was much less than it is today.

von Storch *et al*. (2004) used a coupled atmosphere-ocean model simulation of the climate of the past millennium as a surrogate climate to test the skill of the empirical reconstruction methods used by Mann *et al*. (1998, 1999) in deriving their thousand-year "hockey stick" temperature history of the Northern Hemisphere. They generated several pseudo-proxy temperature records by sampling a subset of the model's simulated grid-box temperatures representative of the spatial distribution of the real-world proxy temperature records used by Mann *et al*. They degraded these pseudo-proxy records with statistical noise, regressed the results against the measured temperatures of the historical record, and used the relationships thus derived to construct a record they could compare against their original model-derived surrogate temperature history.

The six scientists discovered the centennial variability of Northern Hemisphere temperature was underestimated by the regression-based methods they applied, suggesting past variations in real-world temperature "may have been at least a factor of two larger than indicated by empirical reconstructions."

The consequences of this result are readily evident in the reduced degree of Little Ice Age cooling and Medieval warming that resulted from the techniques employed by Mann *et al*.

In an accompanying commentary on von Storch *et al*.'s paper, Osborn and Briffa (2004) state, "if the true natural variability of [Northern Hemisphere] temperature is indeed greater than is currently accepted, the extent to which recent warming can be viewed as 'unusual' would need to be reassessed." The need for this reassessment is also suggested by what von Storch *et al*. refer to as "empirical methods that explicitly aim to preserve low-frequency variability (Esper *et al*., 2002)," which show much more extreme Medieval warming and Little Ice Age cooling than do the reconstructions of Mann *et al*.

These observations indicate the temperature record of Esper *et al*. is likely to be much more representative of reality than is the IPCC-endorsed record of Mann *et al*. The lion's share of the warming experienced since the end of the Little Ice Age occurred well before mankind's CO_2 emissions significantly perturbed the atmosphere, suggesting most of the post-Little Ice Age warming was due to something other than rising atmospheric CO_2 concentrations. That further suggests the lesser warming of the latter part of the twentieth century also may have been due to something else.

Cook *et al*. (2004) reviewed the work of Esper *et al*. (2002) and conducted further analyses of the data the latter team of scientists had employed in its reconstruction effort. Cook *et al.* determined the "strongly expressed multi-centennial variability [of the Esper *et al*. reconstruction] is highly robust over the AD 1200–1950 interval, with strongly expressed periods of 'Little Ice Age' cooling indicated prior to AD 1900," and "persistently above-average temperatures in the AD 960–1050 interval also suggest the large-scale occurrence of a 'Medieval Warm Period' in the Northern Hemisphere extra-tropics."

Cook *et al*. draw this conclusion despite what they describe as strong criticism personally communicated to them by R.S. Bradley of the Mann *et al*. group of researchers. The existence of a global Medieval Warm Period is hotly debated and critical to the climate change debate, because if Earth was as warm as it is today a thousand or more years ago, when the air's CO_2 concentration was more than 100 ppm less than it is today, there is no compelling reason to believe atmospheric CO_2 concentrations had anything to do with the global warming of the past century.

Moberg *et al*. (2005) presented a new temperature history of the Northern Hemisphere spanning the past two millennia, produced from two sources of paleoclimatic data: tree rings, which capture very high frequency climate information, and lake and ocean sediments, which "provide climate information at multi-centennial timescales that may not be captured by tree-ring data."

The new temperature history clearly revealed the existence of one full cycle of the roughly 1500-year climatic oscillation that reverberates throughout the Holocene and across prior glacial and interglacial periods alike (Oppo *et al*., 1998; Raymo *et al*., 1998; McManus *et al*., 1999). Moberg *et al*. noted, for example, "high temperatures—similar to those observed in the twentieth century before 1990—occurred around AD 1000 to 1100, and minimum temperatures that are about 0.7°C below the average of 1961–90 occurred around AD 1600," whereas the twentieth century has seen a return to a new period of relative warmth.

Moberg *et al*. say the low-frequency variability missing from the temperature reconstructions of Mann *et al*. originates from a set of 11 non-tree-ring proxy climate records that cover most of the past two millennia, nine of which already had been calibrated to local/regional temperatures by their developers. Moberg *et al*. say simple averages of temperature proxy series, such as the ones they used, "can yield adequate estimates of Northern Hemisphere century-scale mean-temperature anomalies," citing the work of von Storch *et al*. (2004). When simple averaging is all that is done, as is evident in Moberg *et al*.'s graphical results, the Medieval Warm Period is observed to peak just prior to AD 900 and is strongly expressed between about AD 600 to 1100, very possibly the most correct temperature reconstruction of all (see Figure 4.2.3.1).

Figure 4.2.3.1 shows the final twentieth century temperature of the record developed by Moberg *et al.* is cooler than the temperatures of the entire 500-year time span of the MWP. It is only when the directly measured instrumental temperatures of the latter part of the twentieth century are added to the new temperature history that the Swedish and Russian scientists observe a recent ("post-1990") modern warming that "appears to be unprecedented" over the prior two millennia. Note they say the warming *appears* to be unprecedented, for one cannot make a definitive comparative judgment on the matter when the two types of data involved are significantly different from each other. One cannot compare real apples with reconstructed oranges, especially when the apples may have been contaminated by a factor (the growing urban heat island and land-use change effects) that likely had little or no influence on the oranges.

McIntyre and McKitrick (2005) also analyzed the procedures used by Mann *et al*. (1998) to develop their hockey stick temperature reconstruction. In an analysis of an unusual data transformation employed by Mann *et al*., which strongly affects the resulting principal components (PCs) of their tree-ring-based temperature reconstructions, the two researchers discovered the unusual method nearly always produced a hockey stick-shaped first principal component (PC1) when tested on persistent red noise. “In effect,” they write, “the Mann *et al*. (1998) data transformation results in the PC algorithm mining the data for hockey stick patterns.”

The researchers also demonstrate the data transformation used by Mann *et al*. “effectively selects only one species (bristlecone pine) into the critical North American PC1, making it implausible to describe it as the ‘dominant pattern of variance.’” The selected tree-ring records were ones that had been developed and analyzed by Graybill and Idso (1993), who suggested they were particularly good candidates for exhibiting CO_2-induced increases in growth as opposed to temperature-induced increases in growth, as assumed by Mann *et al*. Graybill and Idso describe in detail how they investigated “the possibility that changes in climate during the past century might be responsible for the unusual increases in ring width growth” that were exhibited by the trees, “considering temperature, precipitation and computed drought values,” and it is their stated conclusion—clearly available for Mann *et al*. to read before using their data—that “it is notable that trends of the magnitude observed in 20th century ring width growth are conspicuously lacking in all of the time

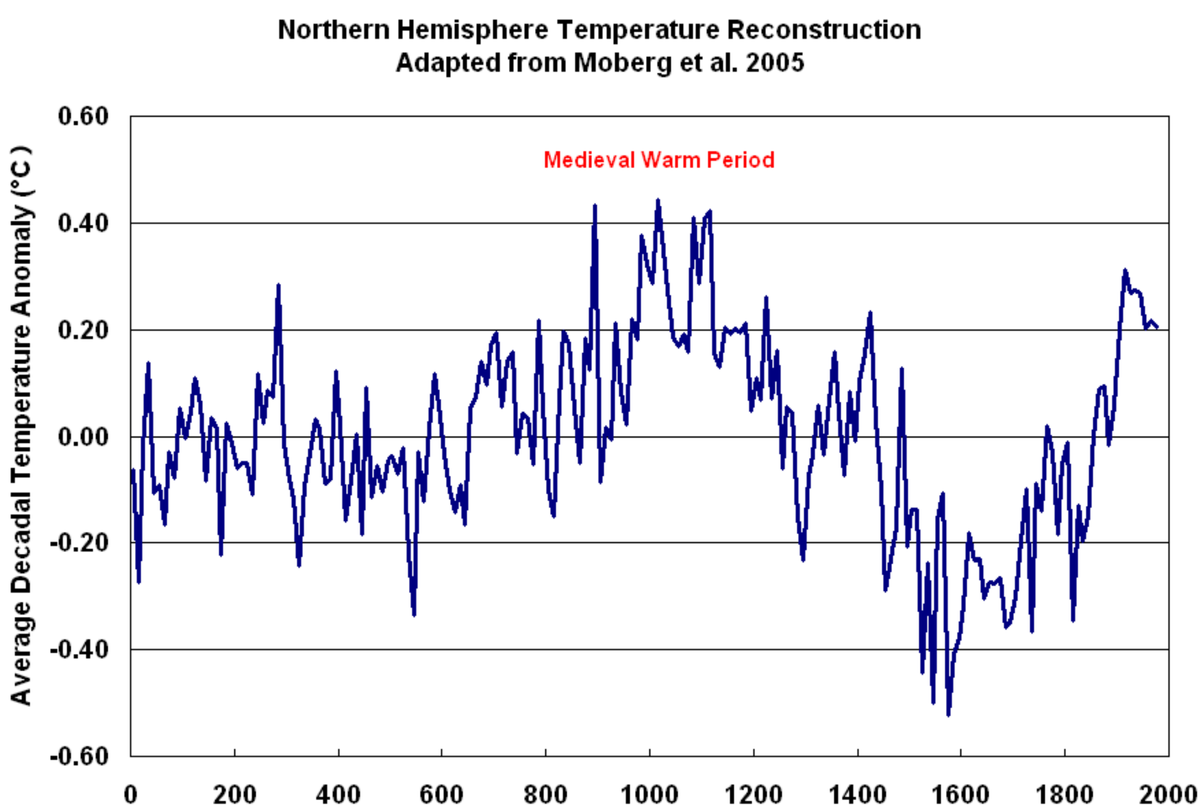

Figure 4.2.3.1. Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data covering the past 2,000 years. Adapted from Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617.

series of instrumented climatic variables that might reasonably be considered growth-forcing in nature." These facts are particularly "disquieting," as McIntyre and McKitrick put it, "given that the NOAMER PC1 has been reported to be essential to the shape of the Mann *et al*. (1998) Northern Hemisphere temperature reconstruction."

McIntyre and McKitrick also show the Mann *et al*. (1998) benchmarks for significance of their Reduction of Error statistic were "substantially under-stated," and using a range of cross-validation statistics, they show Mann *et al*.'s reconstruction "lacks statistical significance."

Esper *et al*. (2005) selected four representations of Earth's surface air temperature history over the past thousand years (Jones *et al*., 1998; Mann *et al*., 1999; Briffa, 2000; Esper *et al*., 2002) for inclusion in an analysis designed to reveal the significance of problems associated with some of those histories. They note "these records were developed using tree ring data alone or using multi-proxy data, and are reported to represent different regions (e.g. Northern Hemisphere (NH) extra-tropics, or full NH)," thereby highlighting two of several factors (different types of data, different areas of applicability) that lead to different results. The four researchers also investigated methodological differences, including "using scaling or regression, the calibration time period, and smoothing data before calibration." They also point out different histories sometimes represent different seasons of the year; they either include or exclude sea surface temperatures; the available data are "more uncertain back in time"; and the record "becomes biased towards Europe, North America, and areas in Asia" moving back in time.

Reporting on the results of their analyses of the effects of scaling and regression approaches applied in the recent scientific literature to proxy-based temperature records, Esper *et al*. (2005) state, "these various approaches alone can result in differences in the reconstructed temperature amplitude ["measured from the coldest to warmest decades"] of about 0.5°C." This difference, they write, is "equivalent to the mean annual temperature change for the Northern Hemisphere reported in the last IPCC report for the 1000–1998 period." In addition, they point out "consideration of temporally changing spatial coverage and uncertainty in both the instrumental and proxy data, as expressed by confidence limits accompanying such records, would further increase the range of amplitude estimates over the past millennium."

Esper *et al*. also note, "when linear regression is used for calibration, the variance of a proxy record remains below that of the target data, leaving the visual impression that the recent dynamics are substantially larger than the historic ones when splicing such records together," which is precisely the impression conveyed when the modern instrumental record is attached to the end of calibrated proxy data, as in the hockey stick temperature record of Mann *et al*. (1999).

Asami *et al*. (2005) derived a monthly resolved 213-year (1787–2000) time series of carbon and oxygen isotope variations measured in a 273-cm-long coral core retrieved from a *Porites labata* colony located on the northwestern coast of Guam, where it had been exposed to open sea surface conditions over the entire period of its development. "On the basis of the Guam δ^{18}O coral record," according to the six scientists, "the early 19th century (1801–1820) was the coolest in the past 210 years, which is consistent with SST reconstructions from a δ^{18}O coral record from New Caledonia (Crowley *et al*., 1997)." This period, they write, "was characterized by a decrease in solar irradiance (Lean *et al*., 1995; Crowley and Kim, 1996) and by a series of large volcanic eruptions in 1808–1809 and 1818–1822 (Crowley *et al*., 1997)." From the early nineteenth century on, "the long-term δ^{18}O coral trend is characterized by its overall depletion throughout the period," indicative of a gradual warming of approximately 0.75°C.

The existence of the Little Ice Age, missing from the Mann *et al.* (1998, 1999) reconstruction, is clearly manifest at the beginning of the Guam coral record and at about the same time in the New Caledonia coral record. The Guam coral record also depicts essentially continuous warming from about 1815, just as the Esper *et al*. record does, whereas the Mann *et al*. record does not depict warming until after 1910, about a century later. A 0.75°C rise in temperature from the start of the warming until the end of the twentieth century is not at all unusual, since it begins at one of the coldest points of the coldest multi-century period (the Little Ice Age) of the entire Holocene, the current interglacial.

The extreme cold of the early 1800s and the warming that followed it were not caused by changes in the air's CO_2 concentration. Instead, a reversal of the forces that produced the cold in the first place (Asami *et al*. mention a decrease in solar irradiance and large volcanic eruptions) likely led to the subsequent warming. This represents the entirely natural recovery of Earth from the global chill of one of the coldest portions of the coldest multi-century period of the past 10,000 years.

D'Arrigo *et al*. (2006) note the Northern Hemispheric temperature reconstruction of Mann *et al*. (1999) "demonstrates minimal temperature amplitude (e.g., during the 'Medieval Warm Period' and 'Little Ice Age') while others (Briffa, 2000; Esper *et al*., 2002; Cook *et al*., 2004; Moberg *et al*., 2005) exhibit more pronounced variability." To determine the reasons for this discrepancy, they assembled mostly tree-ring width (but some density) data from living and subfossil wood of coniferous tree species found at 66 high-elevation and latitudinal treeline North American and Eurasian sites, analyzing these data via both standard (STD) and regional curve standardization (RCS) detrending techniques. STD (used by Mann *et al*.) does not accurately capture the low-frequency variability required to compare the temperatures of periods separated in time by many hundreds of years or more. In addition, D'Arrigo *et al*. report, "the North American data are much improved with new or extended millennial-length records and updates of most of the data sets until at least the late 1990s." Also, they did not use the long bristlecone pine datasets from Colorado and California that Mann *et al*. employed, "as many appear to portray a mixed precipitation and temperature signal (in addition to a purported CO_2 fertilization effect)," and they did not use the Mackenzie Mountains, Boreal, Upperwright, and Gotland datasets utilized by Esper *et al*. (2002) because they "(1) did not demonstrate a significant temperature signal on the local to regional scale, (2) displayed significant correlations with precipitation, or (3) were located at lower latitudes than those compiled for the present analysis."

D'Arrigo *et al*.'s STD and RCS Northern Hemisphere temperature reconstructions spanned the period AD 713–1995. They found "the long-term trends of the STD reconstruction most closely match the Mann *et al*. (1999) and Jones *et al*. (1998) series, whereas the RCS reconstruction compares best with the Esper *et al*. (2002) and Cook *et al*. (2004) series." This observation, they write, "validates the hypothesis (Esper *et al*., 2004) that one reason for the relative lack of long-term variability in the work of Mann *et al*. (1999) was their use of standard detrending procedures that removed low-frequency variation." They conclude "the RCS reconstruction is superior to the more traditional STD method with regards to the ability to retain low-frequency (centennial to multi-centennial) trends."

In comparing the temperatures of the Medieval Warm Period with those of the Current Warm Period, based on the six longest (>1000 years) chronologies they analyzed, D'Arrigo *et al*. conclude "the recent period does not look particularly warmer compared to the MWP." They note the mean of the six series does depict a warmer CWP, but they describe this apparent relationship as "a bias/artifact in the full RCS reconstruction (and likely in many of the other reconstructions) where the MWP, because it is expressed at different times in the six long records, is 'averaged out' (i.e., flattened) compared to the recent period which shows a much more globally consistent signal."

D'Arrigo *et al*. conclude "not enough proxy records yet exist for this time," meaning the MWP. Working with the records they had, they found "late twentieth century warming exceeds peak MWP conditions by 0.67°C when comparing decadal averages (960–969 (reconstruction) = -0.12°C versus 1991–2000 (instrumental) = 0.55°C)." This conclusion, of course, is based on an "apples and oranges" comparison, and the three researchers report, "peak twentieth century warmth for the period covered only by the proxy data (1937–1946, 0.17°C) exceeds peak MWP conditions by 0.29°C," a significantly smaller number than that obtained by comparing the reconstructed and instrumental results.

A further confounding fact, according to D'Arrigo *et al*., is the "apparent decrease in recent temperature sensitivity for many northern sites ... with divergence from instrumental temperatures after ~1986." So great has this divergence been that the late 1990s instrumental temperatures are essentially a full degree Centigrade higher than those of the proxy reconstructions. The three researchers conclude, "until valid reasons for this phenomenon have been found, [we] can only question the ability of tree-ring data to robustly model earlier periods that could have been similarly warm (or warmer) than the present." To resolve the issue of the relative warmth of the CWP compared to that of the MWP, they suggest "many long records from new NH locations and updating of existing records to the present are required."

D'Arrigo *et al*. (2008) tackled the divergence problem, which they describe as "an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings." This problem was "detected in tree-ring width and density records from many circumpolar northern latitude sites since around the middle 20th century." They "review[ed] the current literature published on the divergence problem to date, and assess[ed] its possible causes and implications."

The four researchers identified several possible causes for the divergence: moisture stress, nonlinear or threshold responses to warming, local pollution, delayed snowmelt, changes in seasonality, differential responses to maximum and minimum temperatures, global dimming, methodological issues related to "end effects," biases in instrumental target data, the modeling of such data, declining stratospheric ozone concentrations, increased UV-B radiation at ground level, and "an upward bias in surface thermometer temperature measurements in recent years related to heat island effects."

D'Arrigo *et al*. report their review "did not yield any consistent pattern that could shed light on whether one possible cause of divergence might be more likely than others," leading them to conclude "a combination of reasons may be involved that vary with location, species or other factors, and clear identification of a sole cause for the divergence is probably unlikely."

Ljungqvist (2010) developed a 2,000-year temperature history of the extra-tropical portion of the Northern Hemisphere (i.e., that part covering the latitudinal range 30–90°N) based on 30 temperature-sensitive proxy records with annual to multi-decadal resolution: two historical documentary records, three marine sediment records, five lake sediment records, three speleothem $\delta^{18}O$ records, two ice-core $\delta^{18}O$ records, four varved thickness sediment records, five tree-ring width records, five tree-ring maximum latewood density records, and one $\delta^{13}C$ tree-ring record. Ljungqvist did not employ tree-ring width records from arid and semi-arid regions, because they may have been affected by drought stress and thus may not have shown a linear response to warming if higher summer temperatures also reduced the availability of water, as suggested by the work of D'Arrigo *et al*. (2006) and Loehle (2009).

The results of the Swedish scientist's efforts are depicted in Figure 4.2.3.2. Ljungqvist states this tempereatue history depicts "a Roman Warm Period *c.* AD 1–300, a Dark Age Cold Period *c.* AD 300–800, a Medieval Warm Period c. AD 800–1300 and a Little Ice Age c. AD 1300–1900, followed by the twentieth-century warming." These alternating

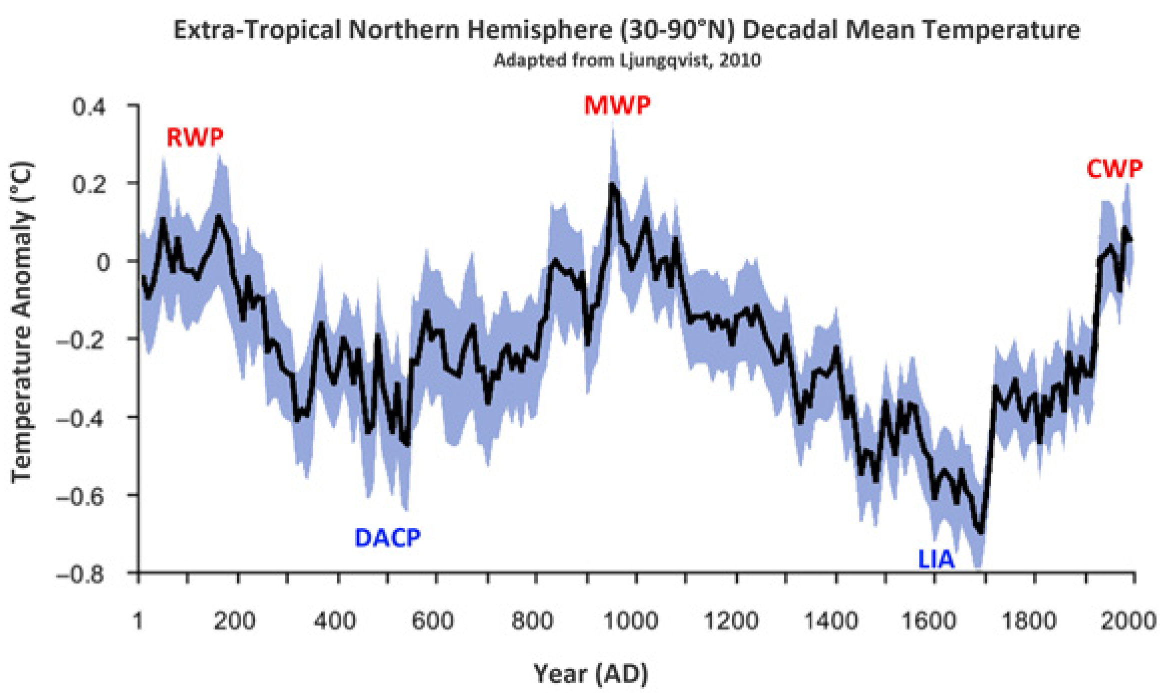

Figure 4.2.3.2. Reconstructed extra-tropical (30-90°N) mean decadal temperature variations relative to the 1961-1990 mean of the variance-adjusted 30-90°N CRUTEM3+HadSST2 instrumental temperature data of Brohan et al.(2006) and Rayner et al. (2006). Adapted from Ljungqvist, F.C. 2010. A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler* **92A**: 339–351.

warm/cold periods, he writes, "probably represent the much discussed quasi-cyclical *c.* 1470 ± 500-year Bond Cycles (Bond and Lotti, 1995; O'Brien *et al.*, 1995; Bond *et al.*, 1997, 2001; Oppo, 1997)," which "affected both Scandinavia and northwest North America synchronically (Denton and Karlen, 1973)" and have "subsequently also been observed in China (Hong *et al.*, 2009a,b), the mid-latitude North Pacific (Isono *et al.*, 2009) and in North America (Viau *et al.*, 2006), and have been shown to very likely have affected the whole Northern Hemisphere during the Holocene (Butikofer, 2007; Wanner *et al.*, 2008; Wanner and Butikofer, 2008), or even been global (Mayewski *et al.*, 2004)."

Ljungqvist also notes "decadal mean temperatures in the extra-tropical Northern Hemisphere seem to have equaled or exceeded the AD 1961–1990 mean temperature level during much of the Roman Warm Period and the Medieval Warm Period," and "the second century, during the Roman Warm Period, is the warmest century during the last two millennia." In addition, "the highest average temperatures in the reconstruction are encountered in the mid to late tenth century," during the Medieval Warm Period. He warns the temperature of the last two decades "is possibly higher than during any previous time in the past two millennia," but adds, "this is only seen in the instrumental temperature data and not in the multi-proxy reconstruction itself."

Ljungqvist's study is especially important because it utilizes "a larger number of proxy records than most previous reconstructions" and "substantiates an already established history of long-term temperature variability."

Syun-Ichi Akasofu (2010), founding director of the International Arctic Research Center of the University of Alaska-Fairbanks (USA), employed "openly available data on sea level changes, glacier retreat, freezing/break-up dates of rivers, sea ice retreat, tree-ring observations, ice cores and changes of the cosmic-ray intensity, from the year 1000 to the present" to show Earth's recovery from the Little Ice Age "has proceeded continuously, roughly in a linear manner, from 1800–1850 to the present," with the rate of recovery being about 0.5°C/century. He suggests Earth is "still in the process of recovery from the LIA," being brought about by whatever was responsible for the mean linear warming of the twentieth century as modulated by a "multi-decadal oscillation of a period of 50 to 60 years" that is superimposed upon it and "peaked in 1940 and 2000, causing the halting of warming temporarily after 2000." Extending these two phenomena into the future, Akasofu predicts the non-CO_2-induced temperature increase over the twenty-first century will be 0.5°C ± 0.2°C, rather than the much greater 4°C ± 2°C predicted by the IPCC.

Ljungqvist *et al*. (2012) write, "a number of Northern Hemispheric (NH) temperature reconstructions covering the last 1–2 millennia, using temperature-sensitive proxy data, have been made to place the observed 20th century warming into a long-term perspective." They state, "these studies generally agree on the occurrence of warmer conditions ca. 800–1300 AD and colder conditions ca. 1300–1900 AD, followed by a strong warming trend in the 20th century," noting "the earlier warm period is usually referred to as the Medieval Warm Period ... whereas the later colder period is usually referred to as the Little Ice Age." "Related to this issue," they continue, "is the question of whether or not the current warmth has exceeded the level and geographic extent of the warmth in the last millennium."

Ljungqvist *et al*. developed "a new reconstruction of the spatio-temporal patterns of centennial temperature variability over the NH land areas for the last twelve centuries based on 120 proxy records," which were "retrieved from a wide range of archives including, but not limited to, ice-cores, pollen, marine sediments, lake sediments, tree-rings, speleothems and historical documentary data." With respect to how big an improvement their database is over those used in prior studies of this type in terms of the amount and distribution of data employed, they present a list of antecedent analyses where the number of proxy records used ranged from only three to 46 (compared to their 120), and where the number of records with annual resolution ranged from only three to 30, whereas their study included 49 such annual-resolution records.

The result of Ljungqvist *et al.*'s work is depicted in Figure 4.2.3.3. The four Swedish scientists report, "during the 9th to 11th centuries there was widespread NH warmth comparable in both geographic extent and level to that of the 20th century." They also note their results indicate "the rate of warming from the 19th to the 20th century is clearly the largest between any two consecutive centuries in the past 1200 years," but this is not surprising, given that the Little Ice Age is universally recognized as having been the coldest multi-century period of the current interglacial (Barclay *et al*., 2009; Briner *et al*., 2009; Menounos *et al*., 2009) and its most extensively glaciated period (Calkin *et al*., 2001;

Clague *et al*., 2004; Joerin *et al*., 2006). Recovery from such an extremely cold condition would be expected to be quite dramatic.

In light of the results depicted in Figure 4.2.3.3, it should be clear there is nothing unusual, unnatural, or unprecedented about Earth's current level of warmth when compared to that of the Medieval Warm Period, when there was significantly less CO_2 in the air than there is currently (~280 ppm then vs. ~400 ppm now). There is no compelling reason to attribute the post-Little Ice Age warming to changes in the concentration of this trace gas of the atmosphere.

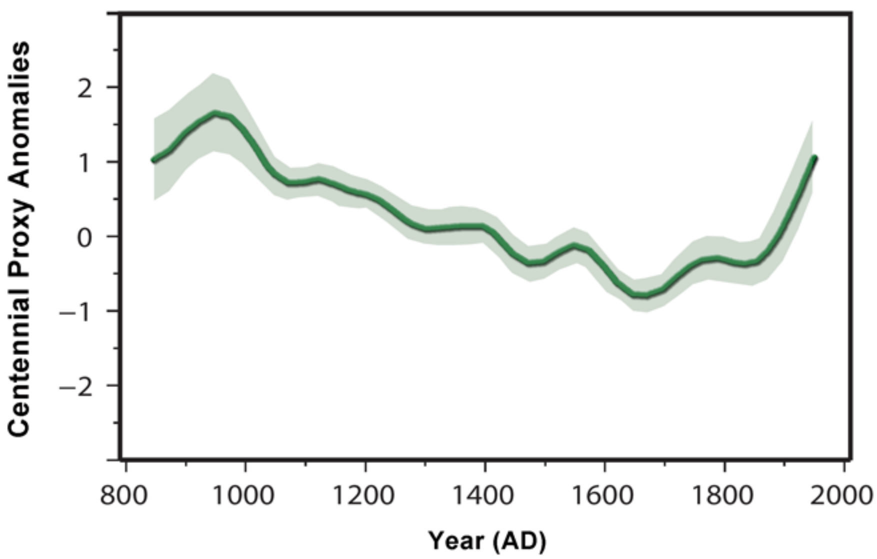

Figure 4.2.3.3. Mean whole-year centennial temperature proxy anomalies (standard deviations from the AD 1000-1899 mean) vs. year AD, where the shaded area represents ± 2 standard errors. Adapted from Ljungqvist, F.C., Krusic, P.J., Brattstrom, G., and Sundqvist, H.S. 2012. Northern Hemisphere temperature patterns in the last 12 centuries. *Climate of the Past* **8**: 227–249.

Christiansen and Ljungqvist (2012) used a variety of temperature proxies "shown to relate to local or regional temperature," together with a reconstruction method shown to "confidently reproduce low-frequency variability," to develop a new multi-proxy reconstruction of the mean temperature of the extratropical Northern Hemisphere (30–90°N) stretching back to the BC/AD transition. This two-millennia-long temperature history shows a well-defined Medieval Warm Period with "a well-defined peak in the period 950–1050 AD with a maximum temperature anomaly of 0.6°C" relative to the reference period of 1880–1960, the timing of which they say "is in agreement with the reconstructions of Esper *et al*. (2002) and Ljungqvist (2010)." They report "the level of warmth during the peak of the MWP in the second half of the 10th century, equal[s] or slightly exceed[s] the mid-20th century warming." This result, they say, is "in agreement with the results from other more recent large-scale multi-proxy temperature reconstructions," citing among others the studies of Moberg *et al*. (2005), Ljungqvist (2010), and Ljungqvist *et al*. (2012).

As for the timing of the MWP in different parts of the extra-tropical Northern Hemisphere, they report Ljungqvist *et al*. (2012) showed, "on centennial time-scales, the MWP is no less homogeneous than the Little Ice Age if all available proxy evidence, including low-resolution records are taken into consideration in order to give a better spatial data coverage."

This research adds to the growing body of real-world evidence demonstrating the global nature and temporal consistency of the MWP. It also confirms the MWP's peak temperatures throughout the extratropical Northern Hemi-sphere strongly rivaled or exceeded those of the Current Warm Period, even though the atmospheric CO_2 concen-trations of today are 40 percent greater than they were during the MWP. Taken together, these observations strongly suggest the warmth of the Current Warm Period is due to something other than the current high atmospheric CO_2 concentration.

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4.2.4 Regional Manifestations of the Non-Uniqueness of Current Temperatures

Sections 4.2.1 through 4.2.3 present evidence temperatures of the past several decades are not unusual, unnatural, or unprecedented on a hemispheric or global scale, contrary to the conclusions of the IPCC. The Roman and Medieval Warm Periods were likely as warm as or warmer than the Current Warm Period. And since temperatures were as warm when atmospheric CO_2 concentrations were much lower than they are now, there are valid empirical reasons to conclude the temperature increase of the past century has occurred independently of the concomitant 40 percent increase in atmospheric CO_2. Real-world observations reveal the Current Warm Period is simply a manifestation of the natural progression of a persistent millennial-scale climate oscillation that regularly brings Earth several-hundred-year periods of modestly higher and lower temperatures independent of variations in atmospheric CO_2 concentration.

In this section, additional evidence is presented by region that there is nothing unusual, unnatural, or unprecedented about current temperatures. Although much of the material focuses on the reality and temperatures of the Roman and Medieval Warm Periods, some discussion is included on temperatures both before and after these important climate epochs.

4.2.4.1 Africa

Based on the temperature and water needs of the crops cultivated by the first agropastoralists of southern Africa, Huffman (1996) constructed a climate history of the region using archaeological evidence acquired from various Iron Age settlements. Dated relic evidence of the presence of cultivated sorghum and millets was considered by Huffman to be so strong as to prove the climate of the subcontinent-wide region must have been warmer and wetter than it is today from approximately AD 900–1300, for these crops cannot be grown in this part of southern Africa under current climatic conditions, which are much too cool and dry.

Other evidence for this conclusion comes from Tyson *et al*. (2000), who obtained a quasi-decadal record of oxygen and carbon-stable isotope data from a well-dated stalagmite of Cold Air Cave in the Makapansgat Valley (30 km southwest of Pietersburg, South Africa). They augmented those data with five-year-resolution temperature data reconstructed from color variations in banded growth-layer laminations of the stalagmite derived from a relationship calibrated against actual air temperatures obtained from a surrounding 49-station climatological network over the period 1981–1995, which had a correlation of +0.78 that was significant at the 99% confidence level. This record revealed a significantly warmer-than-present period that began prior to AD 1000 and lasted to about AD 1300 (see Figure 4.2.4.1.1). Tyson *et al*. report the "maximum warming at Makapansgat at around 1250 produced conditions up to 3–4°C hotter than those of the present."

Holmgren *et al*. (2001) used Cold Air Cave records to derive a 3,000-year temperature record for South Africa that revealed several multi-century warm and cold periods. They found a dramatic warming at approximately AD 900, when temperatures reached a level 2.5°C higher than that prevailing at the time of their analysis of the data (see Figure 4.2.4.1.2).

Holmgren *et al*. (2003) developed a 25,000-year temperature history from a stalagmite retrieved from Cold Air Cave based on $\delta^{18}O$ and $\delta^{13}C$ measurements dated by ^{14}C and high-precision thermal ionization mass spectrometry using the $^{230}Th/^{234}U$ method. The nine researchers found "cooling is evident from ~6 to 2.5ka [thousand years before present, during the long interval of coolness that preceded the Roman Warm Period], followed by warming between 1.5 and 2.5 ka [the Roman Warm Period] and briefly at ~AD 1200 [the Medieval Warm Period, which followed the Dark

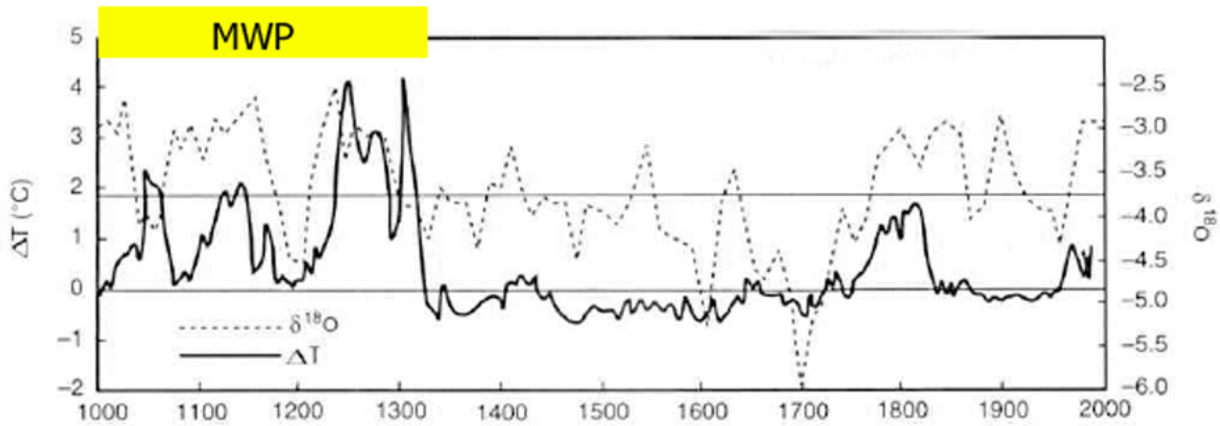

Figure 4.2.4.1.1. Temperature reconstruction from Cold Air Cave in the Makapansgat Valley, South Africa. Adapted from Tyson, P.D., Karlén, W., Holmgren, K., and Heiss, G.A. 2000. The Little Ice Age and medieval warming in South Africa. *South African Journal of Science* **96**: 121–126.

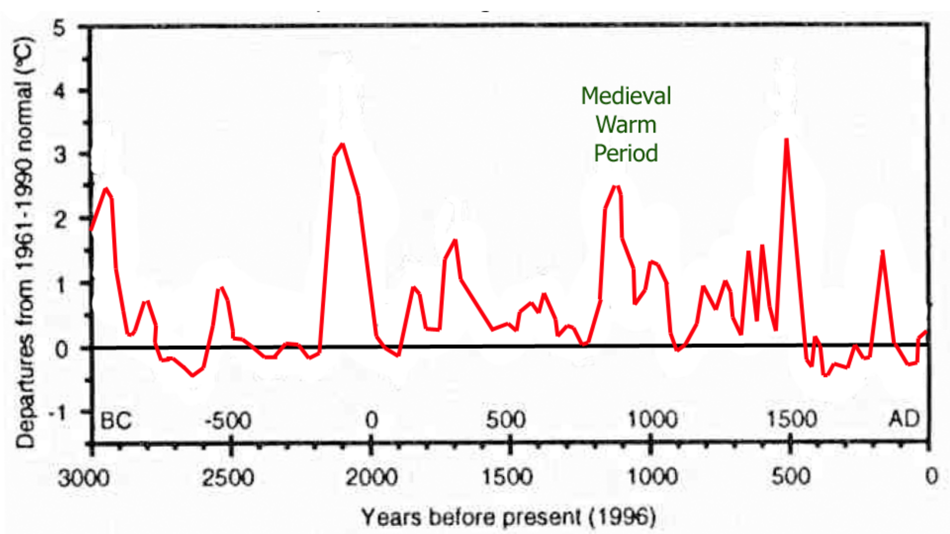

Figure 4.2.4.1.2. Temperature reconstruction from Cold Air Cave in the Makapansgat Valley, South Africa. Adapted from Holmgren, K., Tyson, P.D., Moberg, A., and Svanered, O. 2001. A preliminary 3000-year regional temperature reconstruction for South Africa. *South African Journal of Science* **97**: 49–51.

Ages Cold Period],” after which “maximum Holocene cooling occurred at AD 1700 [the depth of the Little Ice Age].” They also note “the Little Ice Age covered the four centuries between AD 1500 and 1800 and at its maximum at AD 1700 represents the most pronounced negative $\delta^{18}O$ deviation in the entire record.” This temperature record reveals the existence of all of the major millennial-scale oscillations of climate that are evident in data collected from regions surrounding the North Atlantic Ocean.

Working with the vertical sediment profile of Ocean Drilling Program Hole 658C, which was cored off Cap Blanc, Mauritania (20°45’N, 18°35’W) at a water depth of 2,263 meters, DeMenocal *et al*. (2000) analyzed various parameters, including planktonic foraminiferal assemblage census counts, from which they calculated warm- and cold-season sea surface temperatures based on transfer functions derived from faunal analyses of 191 other Atlantic core tops. The authors report finding a series of abrupt millennial-scale cooling events followed by compensatory warming events that “appear to have involved the entire North Atlantic basin (O'Brien *et al*., 1995; Keigwin, 1996; Bond *et al*., 1997; Bianchi and McCave, 1999; Bond *et al*., 1999), recurred with a ~1,500 ± 500 year period throughout glacial and interglacial intervals (O'Brien *et al*., 1995; Bond *et al*., 1997; Bianchi and McCave, 1999; Bond *et al*., 1999), were accompanied by terrestrial climate changes (COHMAP Members, 1988; Gasse and Van Campo, 1999), and involved large-scale ocean and atmosphere reorganizations that were completed within decades or centuries (Alley *et al*., 1993)." The four researchers go on to state, "these climate perturbations continue to persist during 'our time,'" noting "the most recent of these, the Little Ice Age, ended in the late 19th century" and "some of the warming since that time may be related to the present warming phase of this millennial-scale oscillation." They add, "the warming in recent decades is unprecedented relative to the past millennium."

This work further revealed that between about AD 800 and 1050 the "Medieval Warm Period," as they describe it, "was only marginally warmer than present." The graphical presentation of their results (see Figure 4.2.4.1.3) depicts between 0.6 and 1.2°C for the cold and warm season SST estimates, respectively.

Figure 4.2.4.1.3 shows the peak warmth of the Medieval Warm Period, which occurred roughly one thousand years ago, was approximately 1.2°C higher than what their data show for the end of the twentieth century. There is some uncertainty, however, with respect to what year corresponds with the authors' definition of the present. The SST graphic reproduced from their paper indicates the "present" corresponds to around the year 1900, whereas the text of their paper indicates the first data point represents conditions from between a sediment depth of 0 and 2 cm and the core "was continuously subsampled at 2-cm intervals, which is equivalent to between 50 and 100 years temporal resolution." Because of this ambiguity and erring on the side of caution, it can be concluded the MWP warmth was about the same as the warmth of the past two to three decades. This assessment is arrived at by noting the surface air temperature of the globe has warmed by about 0.7 °C over the past 100 years, which falls between the 0.6 and 1.2°C sea surface temperature differential between the peak warmth of the MWP and that of deMenocal *et al*.'s "present."

Lamb *et al*. (2003) provide strong evidence for a hydrologic fingerprint of the Medieval Warm Period in Central Kenya in a study of pollen data obtained

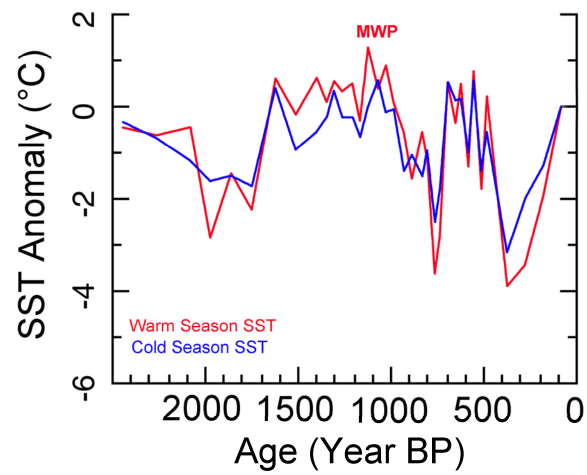

Figure 4.2.4.1.3. West African sea surface temperature vs. time. Adapted from deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M. 2000. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* **288**: 2198–2202.

from a sediment core taken from Crescent Island Crater, a sub-basin of Lake Naivasha. Of particular interest is the strong similarity between their results and those of Verschuren *et al*. (2000). The most striking of these correspondences occurred over the period AD 980 to 1200, when lake level was at a 1,100-year low and woody taxa were significantly underrepresented in the pollen assemblage.

Stager *et al*. (2003) analyzed diatom types and abundances found in a sediment core retrieved from Pilkington Bay, Lake Victoria, East Africa (0°18'N, 33°20'E), relating them to the ratio of precipitation to evaporation (P/E) and/or lake depth. This revealed, they write, "major droughts occurred ca. 1200–600 yr B.P. during Europe's Medieval Warm Period."

Fraedrich *et al*. (1997) examined records of historical maximum and minimum flood-level time series of the River Nile (AD 622–1470) "to identify abrupt climate changes by applying global and local analysis techniques: the Mann-Kendall test and a non-hierarchical cluster analysis method to improve the Mann-Kendall test; a multi-scale moving *t*-test with correction to the degree of freedom and an anti-symmetric wavelet transform." They noted the River Nile and its source regions, with their "links to other climatic zones of the world, may represent a key region to demonstrate the possible global nature of climate variability." The four researchers report "three climate epochs of longer time-scales, AD 622–1078, 1079–1325 and 1326–1470, coinciding with larger-scale climate changes reported in Europe: a relatively cool age, the Little Climatic Optimum of the Middle Ages, and an interim period before the Little Ice Age."

Kondrashov *et al*. (2005) applied advanced spectral methods to fill data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels on the Nile River over the 1,300-year period AD 622–1922. Several statistically significant periodicities were noted, including cycles at 256, 64, 19, 12, 7, 4.2, and 2.2 years. With respect to the causes of these cycles, the three researchers state the 4.2- and 2.2-year oscillations are likely due to El Niño-Southern Oscillation variations, the 7-year cycle may be related to North Atlantic influences, and the longer-period oscillations could be due to astronomical forcings. They also note the annual-scale resolution of their results provides a "sharper and more reliable determination of climatic-regime transitions" in tropical east Africa, including the documentation of fairly abrupt shifts in river flow at the beginning and end of the Medieval Warm Period.

Lamb *et al*. (2007) developed a 2,000-year history of effective precipitation based upon oxygen and carbon isotope and pollen stratigraphy data derived from a sediment core taken from Lake Hayq (11°21'N, 39°43'E) on the eastern margin of the north-central highlands in South Wollo, Ethiopia. This record revealed, they write, a "similar, but slightly moister climate than today, with high interdecadal variability, prevailed from AD 800 to AD 1200, equivalent to the European 'Mediaeval Warm Period,'" and "a period of high effective precipitation followed, from AD 1200 to AD 1700, during the 'Little Ice Age.'" A moister climate was also inferred during the MWP by Vogel (2003), who upon examining radiocarbon-dated stands of dead *Acacia erioloba* trees from locations within the central Namib Desert concluded trees growing near Sossusvlei (24.75°S, 15.28°E) started growing in the eleventh and twelfth centuries "during the relatively humid conditions of the Medieval Warm Period and died out after the more arid conditions of the Little Ice Age set in during the 14th century."

Ngomanda *et al*. (2007) derived high-resolution (<40 years) paleoenvironmental reconstructions for the past 1,500 years based on pollen and carbon isotope data obtained from sediment cores retrieved from Lakes Kamalete and Nguene in the lowland rainforest of Gabon. After a sharp rise at ~1200 cal yr BP, the nine researchers note, "A/H [aquatic/hygrophytic] pollen ratios showed intermediate values and varied strongly from 1150 to 870 cal yr BP, suggesting decadal-scale fluctuations in the water balance during the 'Medieval Warm Period.'" Thereafter, lower A/H pollen ratios "characterized the interval from ~500 to 300 cal yr BP, indicating lower water levels during the 'Little Ice Age.'" In addition, they report, "all inferred lake-level low stands, notably between 500 and 300 cal yr BP, are associated with decreases in the score of the TRFO [Tropical Rainforest] biome."

Ngomanda *et al*. state, "the positive co-variation between lake level and rainforest cover changes may indicate a direct vegetational response to regional precipitation variability," noting "evergreen rainforest expansion occurs during wet intervals, with contraction during periods of drought." In this part of Western Equatorial Africa, it appears the Little Ice Age was a time of low precipitation, low lake levels, and low evergreen rainforest presence, while much the opposite was the case during the Medieval Warm Period, when fluctuating wet-dry conditions led to fluctuating lake levels and a greater evergreen rainforest presence.

Placing these findings within a broader temporal context, Ngomanda *et al*. note "rainforest environments during the late Holocene in western equatorial Africa are characterized by successive millennial-scale changes according to pollen (Elenga *et al*., 1994, 1996; Reynaud-Farrera *et al*., 1996; Maley and Brenac, 1998; Vincens *et al*., 1998), diatom (Nguetsop *et al*., 2004), geochemical (Delegue *et al*., 2001; Giresse *et al*., 1994), and sedimentological data (Giresse *et al*., 2005; Wirrmann *et al*., 2001)," and "these changes were essentially driven by natural climatic variability (Vincens *et al*., 1999; Elenga *et al*., 2004)."

Esper *et al*. (2007) used *Cedrus atlantica* ring-width data "to reconstruct long-term changes in the Palmer Drought Severity Index (PDSI) over the past 953 years in Morocco, Northwest Africa." They report "the long-term PDSI reconstruction indicates generally drier conditions before ~1350, a transition period until ~1450, and generally wetter conditions until the 1970s," after which there were "dry conditions since the 1980s." In addition, they determined "the driest 20-year period reconstructed is 1237–1256 (PDSI = -4.2)," adding, "1981–2000 conditions are in line with this historical extreme (-3.9)." Also of significance, the six researchers note "millennium-long temperature reconstructions from Europe (Buntgen *et al*., 2006) and the Northern

Hemisphere (Esper *et al*., 2002) indicate that Moroccan drought changes are broadly coherent with well-documented temperature fluctuations including warmth during medieval times, cold in the Little Ice Age, and recent anthropogenic warming." The latter coherency suggests the peak warmth of the Medieval Warm Period was at least as great as that of the last two decades of the twentieth century throughout the entire Northern Hemisphere. If the coherency is strictly interpreted, it suggests the warmth of the MWP was even greater than that of the late twentieth century.

Working with sediment cores extracted from East Africa's Lake Tanganyika near the remote and sparsely settled Mahale Mountains (6°33.147'S, 29°58.480'E), Tierney *et al*. (2010) developed a 1,500-year history of lake-surface water temperature (LST) using the TEX86 proxy technique, which relates the degree of cyclization of aquatic archaeal glycerol dialkyl glycerol tetraethers found in membrane lipids of certain marine picoplankton to LST. This work revealed the existence of "a period of extended warmth between AD 1100 and 1400," which clearly represents the Medieval Warm Period. The peak LST of this period was 1.4°C cooler than the peak LST at the end of the twentieth century.

Kuhnert and Mulitza (2011) derived sea surface temperatures from Mg/Ca ratios of *Globigerinoides ruber* foraminifers extracted from gravity core GeoB 9501-5 recovered off southern Mauritania at 16°50'N, 16°44'W from a water depth of 323 m during Meteor cruise M65/1, described by Mulitza (2006), using the calibration for the 250–350 µm fraction of *G. ruber* (pink) from Anand *et al*. (2003) to produce a 1,700-year summer–fall SST history. Between AD 850 and AD 1150, Kuhnert and Mulitza identify a period of warmth they equate with the Medieval Warm Period, the peak 50-year mean SST of which was 1.1°C greater than the corresponding 50-year mean SST at the end of the record, which had been trending upward over the prior half-century.

The research findings summarized here suggest the Medieval Warm Period occured over wide reaches of Africa and was probably more extreme in Africa than the Current Warm Period has been to this point in time.

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4.2.4.2 Antarctica

The IPCC has long predicted CO_2-induced global warming, which they assert has accelerated significantly over the twentieth century and is unprecedented in the past millennium or more, should be greatly amplified in Earth's polar regions. The IPCC has claimed the following:

> Robust evidence for polar amplification in either one or both hemispheres has been found in climate model experiments of past and future climate change, paleo-climate data and recent instrumental temperature records" (Second Order Draft of AR5, dated October 5, 2012, p. 5–14).

The research reviewed in this section shows the IPCC's claim of "robust evidence" of amplified CO_2-induced warming in Earth's polar regions is patently incorrect, as their thesis has been invalidated by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies of Antarctica demonstrate the atmosphere's CO_2 concentration is not a major player in bringing about significant changes in Earth's climate.

4.2.4.2.1 The Past Few Centuries through the Past Few Millennia

The study of Antarctic temperatures has provided valuable insight into global climate change. Key among early pertinent findings was the observation of a large-scale correlation between proxy air temperature and atmospheric CO_2 measurements obtained from ice cores drilled in the interior of the continent. In the mid- to late-1980s, this broad correlation dominated much of the climate change debate and led many to claim the gross CO_2-temperature correlation proved changes in atmospheric CO_2 concentration caused corresponding changes in air temperature, and future increases in the air's CO_2 content due to anthropogenic CO_2 emissions would therefore intensify global warming.

This contention was challenged by Idso (1989), who wrote in reference to the data used to support the claim, "changes in atmospheric CO_2 content never precede changes in air temperature, when going from glacial to interglacial conditions; and when going from interglacial to glacial conditions, the change in CO_2 concentration actually lags the change in air temperature (Genthon *et al*., 1987)." He concludes "changes in CO_2 concentration cannot be claimed to be the cause of changes in air temperature, for the appropriate sequence of events (temperature change *following* CO_2 change) is not only never present, it is actually violated in [at least] half of the record (Idso, 1988)."

Petit *et al*. (1999) reconstructed histories of surface air temperature and atmospheric CO_2 concentration from data obtained from a Vostok ice core that covered the prior 420,000 years, determining "the CO_2 decrease lags the temperature decrease by several thousand years" during glacial inception and "the same sequence of climate forcing operated during each termination." Fischer *et al*. (1999), working with sections of ice core records from the most recent three glacial terminations, found "the time lag of the rise in CO_2 concentrations with respect to temperature change is on the order of 400 to 1000 years during all three glacial-interglacial transitions."

By the turn of the century, ice-coring instrumentation and techniques had improved considerably, and newer studies with finer temporal resolution began to reveal increases (decreases) in air temperature drive increases (decreases) in atmospheric CO_2 content and not vice versa, as suggested, for example, by the work of Indermuhle *et al*. (2000) and Monnin *et al*. (2001). A good example of this relationship was provided by Caillon *et al.* (2003), who showed during Glacial Termination III "the CO_2 increase lagged Antarctic deglacial warming by 800 ± 200 years." Although this finding "confirms that CO_2 is not the forcing that initially drives the climatic system during a deglaciation," they and many others continued to argue the subsequent increase in atmospheric CO_2—believed to be due to warming-induced CO_2 outgassing from the world's oceans—serves to amplify the warming caused by whatever it is that prompts the temperature to rise in the first place. This conviction, however, is founded on unproven assumptions about the strength of CO_2-induced warming, and it is applied without any regard for biologically induced negative climate feedbacks that can occur in response to atmospheric CO_2 enrichment.

Yoon *et al.* (2002) write, "the maritime record on the Antarctic Peninsula shelf suggests close chronological correlation with Holocene glacial events in the Northern Hemisphere, indicating the possibility of coherent climate variability in the Holocene." Similarly, Khim *et al.* (2002) state, "two of the most significant climatic events during the late Holocene are the Little Ice Age (LIA) and Medieval Warm Period (MWP), both of which occurred globally (Lamb, 1965; Grove, 1988)," further noting "evidence of the LIA has been found in several studies of Antarctic marine sediments (Leventer and Dunbar, 1988; Leventer *et al.*, 1996; Domack *et al.*, 2000)." Khim *et al.*'s paper can be added to this list of scientific journal articles documenting the existence of the LIA in Antarctica, for it also demonstrates the presence of the MWP in Antarctica, as well as earlier cold and warm periods of similar intensity and duration.

As more studies have been conducted, it has become increasingly clear these several-hundred-year cold and warm periods were not confined to lands bordering the North Atlantic Ocean, as the IPCC suggests. These periods clearly were global, and they demonstrate the reality of the likely solar-induced millennial-scale climatic oscillation that is manifest in the post-1850 warming of the world.

Stenni *et al.* (2002) examined several paleoclimatic indicators in two firn cores retrieved from the Talos Dome area of East Antarctica in 1996, with accurate dating provided by non-sea-salt sulfate spikes associated with well-documented volcanic eruptions and tritium activity associated with known atmospheric thermonuclear bomb tests. The results of their work were compared with those based on other East Antarctic ice core records obtained from Dome C EPICA, Taylor Dome, and the South Pole. The seven scientists state the several records suggest "cooler climate conditions between the middle of [the] 16th and the beginning of [the] 19th centuries, which might be related to the Little Ice Age (LIA) cold period." After discussing other findings, they conclude "more and more evidence coming from ice core records, glacier extension and other proxy records are leading to the idea that the Antarctic continent or at least East Antarctica also experienced the LIA cool episode."

Cremer *et al.* (2003) reconstructed a history of environmental change in the southern Windmill Islands, East Antarctica, based upon diatom assemblages obtained from two long and well-dated sediment cores removed from two marine bays, comparing their findings with those of studies of several other parts of Antarctica. The four researchers note, "the diatom assemblage in the upper sediments of both cores indicates Neoglacial cooling from ~1000 cal yr BP," and this latest thousand-year period "is generally marked by distinct cooling leading to glacial re-advances, more extensive sea-ice, lower precipitation, and lower bioproductivity." In addition, they report "this climatic deterioration is visible in nearly all available Antarctic terrestrial and marine records (e.g. Ingolfsson *et al.*, 1998; Jones *et al.*, 2000; Roberts *et al.*, 2000, and references therein)."

Hemer and Harris (2003) extracted a sediment core from beneath the Amery Ice Shelf, East Antarctica, about 80 km landward of its present edge. In analyzing the core's characteristics over the past 5,700 ^{14}C years, the two scientists observed a peak in absolute diatom abundance in general, and the abundance of *Fragilariopsis curta* in particular. These parameters, they write, "are associated with increased proximity to an area of primary production, such as the sea-ice zone" at about 750 ^{14}C yr B.P., which puts the time of maximum Ice Shelf retreat in close proximity to the Medieval Warm Period.

Roberts *et al.* (2004) conducted a fossil diatom analysis of an 82-cm sediment core covering the approximate time period 2,000–1,700 ^{14}C yr BP, removed from the deepest part of Beall Lake in the northern Windmill Islands in one of the more significant ice-free oases on the East Antarctic coastline. Samples of the core were radiocarbon dated and corrected for the Antarctic reservoir effect. Based on the species of diatoms found in this sample, Roberts *et al.* inferred the existence of a multi-centennial period of warmth characterized by summer temperatures "much higher than present summer temperatures." Supporting this inference, they also note observations made at both Casey and Law Dome indicated "during the late Holocene, a warm period existed with precipitation and summer temperatures higher than at present (Goodwin, 1993)." They conclude, "the diatom-inferred Holocene palaeosalinity record from Beall Lake indicates the late Holocene warm period was much warmer than at present." The dates they give for this period suggest it was part of the Roman Warm Period.

Hall *et al*. (2006) collected skin, hair, and whole-body mummified remains from Holocene raised-beach excavations at locations along Antarctica's Victoria Land Coast, which they identified by visual inspection and DNA analysis as coming from southern elephant seals (*Mirounga leonina*) and which they analyzed for age by means of radiocarbon dating. Data from 14 locations within the region of study, which they describe as being "well south" of the seals' current "core sub-Antarctic breeding and molting grounds," indicate the period of time they denominate the Seal Optimum began about 600 BC and ended about AD 1400, "broadly contemporaneous with the onset of Little Ice Age climatic conditions in the Northern Hemisphere and with glacier advance near [Victoria Land's] Terra Nova Bay," although they found evidence of southern elephant seal presence stretching back to the mid-Holocene.

The U.S., British, and Italian researchers say their findings indicate "warmer-than-present climate conditions" at the times and locations of the southern elephant seal presence and "if, as proposed in the literature, the [Ross] ice shelf survived this period, it would have been exposed to environments substantially warmer than present." Their data also indicate this warmth, which began with the inception of the Roman Warm Period and ended with the demise of the Medieval Warm Period, was so significant that the intervening Dark Ages Cold Period was not intense enough to drive the seals from Antarctica.

Khim *et al*. (2002) analyzed a sediment core removed from the eastern Bransfield Basin just off the northern tip of the Antarctic Peninsula for grain size, total organic carbon content, magnetic susceptibility, biogenic silica content, ^{210}Pb geochronology, and radiocarbon (^{14}C) age. These data clearly depicted the presence of the "Little Ice Age and Medieval Warm period, together with preceding climatic events of similar intensity and duration," they write.

Hall *et al*. (2010) write, "over the past 50 years, the Antarctic Peninsula warmed ~2°C" and resultant rapid ice breakups "have destroyed several small, thin ice shelves fringing the Antarctic Peninsula (i.e., Cook and Vaughan, 2009, and references therein)," leading them to ask, "is the recent warming of the Antarctic Peninsula unique in the Holocene?" The three researchers "examined organic-rich sediments exposed by the recent retreat of the Marr Ice Piedmont on western Anvers Island near Norsel Point," where glaciers "have been undergoing considerable retreat in response to the well-documented warming." They "obtained moss and reworked marine shells from natural sections within 26 meters of the present ice front" as well as "both peat and reworked shells from sediments exposed in a tunnel beneath the residual ice mass," samples of which were radiocarbon-dated and the results converted to calendar years.

The results indicated peat from the overrun sediments dated to between 707 ± 36 and 967 ± 47 cal. yr B.P., which led them to conclude, "ice was at or behind its present position at ca. 700–970 cal. yr B.P. and during at least two earlier times, represented by the dates of shells, in the mid-to-late Holocene." The three researchers say their findings imply "the present state of reduced ice on the western Antarctic Peninsula is not unprecedented." This leads them to pose another important question: "How widespread is the event at 700–970 cal. yr B.P.?"

They observe "Khim *et al*. (2002) noted a pronounced high-productivity (warm) event between 500 and 1000 cal. yr B.P. in magnetic susceptibility records from Bransfield Basin" and "dates of moss adjacent to the present ice front in the South Shetland Islands (Hall, 2007) indicate ice there was no more extensive between ca. 650 and 825 cal. yr B.P. than it is now." They also note "evidence for reduced ice extent at 700–970 cal. yr B.P. is consistent with tree-ring data from New Zealand that show a pronounced peak in summer temperatures (Cook *et al*., 2002)" and "New Zealand glaciers were retracted at the same time (Schaefer *et al*., 2009)." They conclude their findings "are compatible with a record of glacier fluctuations from southern South America, the continental landmass closest to Antarctica (Strelin *et al*., 2008)." It would appear much of the southernmost portion of Earth experienced a period of significantly enhanced warmth within the broad timeframe of the planet's global MWP.

Lu *et al*. (2012) constructed "the first downcore

$\delta^{18}O$ record of natural ikaite hydration waters and crystals collected from the Antarctic Peninsula (AP)" they say were "suitable for reconstructing a low resolution ikaite record of the last 2000 years." According to the group of nine UK and U.S. researchers, ikaite "is a low temperature polymorph of calcium carbonate that is hydrated with water molecules contained in its crystal lattice," and they write, "ikaite crystals from marine sediments, if collected and maintained at low temperatures, preserve hydration waters and their intact crystal structures, both of which have the potential to provide isotopic constraints on past climate change."

Lu *et al*. report "the ikaite record qualitatively supports that both the Medieval Warm Period and Little Ice Age extended to the Antarctic Peninsula." They also note the "most recent crystals suggest a warming relative to the LIA in the last century, possibly as part of the regional recent rapid warming," but they add, "this climatic signature is not yet as extreme in nature as the MWP," suggesting even the recent warming of the AP may not have returned that region to the warmth experienced there during the MWP.

Hall and Denton (2002) mapped the distribution and elevation of surficial deposits along the southern Scott Coast of Antarctica in the vicinity of the Wilson Piedmont Glacier, which runs parallel to the coast of the western Ross Sea from McMurdo Sound north to Granite Harbor. The chronology of the raised beaches they studied was determined from more than 60 ^{14}C dates of incorporated organic materials previously collected from hand-dug excavations (Hall and Denton, 1999). The record shows "the Wilson Piedmont Glacier was still less extensive than it is now" near the end of the Medieval Warm Period, "as late as 890 ^{14}C yr BP."

Bertler *et al*. (2011) obtained new deuterium (δD) data acquired via analysis of the top 50 meters of a 180-meter-long ice core extracted from the ice divide of Victoria Lower Glacier in the northernmost McMurdo Dry Valleys, which they converted to temperature data by means of a temperature-isotope relationship developed by Steig *et al*. (1998) from data obtained from the Taylor Dome ice core record (see Figure 4.2.4.2.1.1). Bertler *et al*. report they identified three distinct time periods in their record: the last 150 years of the Medieval Warm Period (AD 1140 to 1287), the Little Ice Age (AD 1288 to 1807), and the Modern Era (AD 1808 to 2000). With respect to the Medieval Warm Period, they write, "the McMurdo Dry Valleys were 0.35°C warmer during the MWP than during ME, accompanied by warmer conditions in the Ross Sea." The three researchers also note "a magnetic susceptibility record from Palmer Deep marine core (PD92 30MS) also supports warmer MWP conditions, this time in Drake Passage (Domack and Mayewski, 1999)."

Noon *et al*. (2003) used oxygen isotopes preserved in authigenic carbonate retrieved from freshwater sediments of Sombre Lake on Signy Island (60°43'S, 45°38'W) in the Southern Ocean to construct a 7,000-year history of that region's climate. They found the general trend of temperature at the study site has been downward. Approximately 2,000 years ago, after a thousand-year gap in the data, Signy Island experienced the relative warmth of the last vestiges of the Roman Warm Period as delineated by McDermott *et al*. (2001) on the basis of a high-resolution speleothem $\delta^{18}O$ record from southwest Ireland. Then the record shows the Dark Ages Cold period, contemporaneous with what McDermott *et al*. observe in the Northern Hemisphere, after which the Medieval Warm Period appears at the same point in time and persists for the same length of time it does in the vicinity of Ireland, whereupon the Little Ice Age sets in just as it does in the Northern Hemisphere. Finally, there is an indication of late twentieth century warming, still a long way from conditions comparable to those of the Medieval Warm Period (see Figure 4.2.4.2.1.2).

Castellano *et al*. (2005) derived a detailed history of Holocene volcanism from the sulfate record of the first 360 meters of the Dome Concordia ice core that covered the period 0–11.5 kyr BP. They compared their results for the past millennium with similar results obtained from eight other Antarctic ice cores. Before doing so, they normalized the results at each site by dividing its several volcanic-induced sulfate deposition values by the value produced at that site by the AD 1816 Tambora eruption, in order to reduce deposition differences among sites that might have been induced by differences in local site characteristics. This work revealed most volcanic events in the years 1000–1500 AD exhibited greater among-site variability in normalized sulphate deposition than was observed thereafter.

Castellano *et al.* cited Budner and Cole-Dai (2003) in noting "the Antarctic polar vortex is involved in the distribution of stratospheric volcanic aerosols over the continent." Assuming the intensity and persistence of the polar vortex in both the troposphere and stratosphere "affect the penetration of air masses to inland Antarctica, isolating the

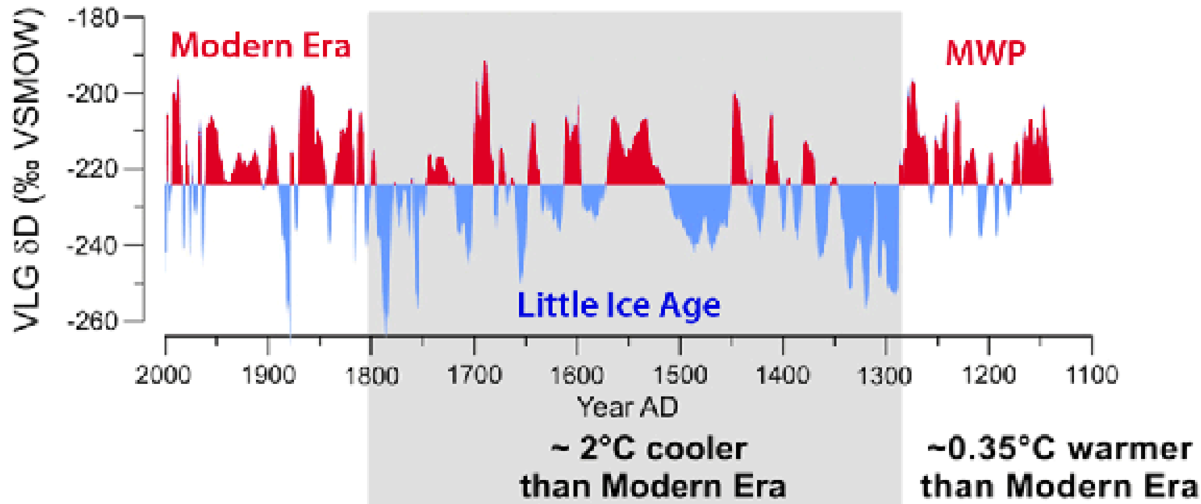

Figure 4.2.4.2.1.1. Deuterium (δD) data acquired from an ice core that had been extracted from the ice divide of Victoria Lower Glacier in the northernmost McMurdo Dry Valleys. Adapted from Bertler, N.A.N., Mayewski, P.A., and Carter, L. 2011. Cold conditions in Antarctica during the Little Ice Age: implications for abrupt climate change mechanisms. *Earth and Planetary Science Letters* **308**: 41–51.

continental area during cold periods and facilitating the advection of peripheral air masses during warm periods (Krinner and Genthon, 1998)," Castellano *et al.* "support the hypothesis that the pattern of volcanic deposition intensity and geographical variability [higher values at coastal sites] could reflect a warmer climate of Antarctica in the early last millennium," and "the re-establishment of colder conditions, starting in about AD 1500, reduced the variability of volcanic depositions."

Castellano *et al*. state "this warm/cold step could be like a Medieval Climate Optimum-like to Little Ice Age-like transition." They additionally cite Goosse *et al*. (2004) as reporting evidence from Antarctic ice-core δD and $\delta^{18}O$ data "in support of a Medieval Warming-like period in the Southern Hemisphere, delayed by about 150 years with respect to Northern Hemisphere Medieval Warming." The researchers conclude by postulating, "changes in the extent and intra-Antarctic variability of volcanic depositional fluxes may have been consequences of the establishment of a Medieval Warming-like period that lasted until about AD 1500."

Hall *et al*. (2006) collected skin, hair, and whole-body mummified remains from Holocene raised-beach excavations at locations along Antarctica's Victoria Land Coast, which they identified by both visual inspection and DNA analysis as coming from southern elephant seals, and which they analyzed for age by radiocarbon dating. They obtained data from 14 locations within their study region, which they describe as being "well south" of the seals' current "core sub-Antarctic breeding and molting grounds." The data indicate the Seal Optimum began about 600 BC and ended about AD 1400; Hall *et al.* describe the latter date as being "broadly contemporaneous with the onset of Little Ice Age climatic conditions in the Northern Hemisphere and with glacier advance near [Victoria Land's] Terra Nova Bay." The U.S., British, and Italian researchers say their findings indicate "warmer-than-present climate conditions" at the times and locations of the southern elephant seal presence and "if, as proposed in the literature, the [Ross] ice shelf survived this period, it would have been exposed to environments substantially warmer than present," which would have included both the Roman Warm Period and Medieval Warm Period.

Williams *et al*. (2007) presented methyl chloride (CH_3Cl) measurements of air extracted from a 300-m ice core obtained at the South Pole, Antarctica, covering the time period 160 BC to AD 1860. The researchers found "CH_3Cl levels were elevated from 900–1300 AD by about 50 ppt relative to the previous 1000 years, coincident with the warm Medieval Climate Anomaly (MCA)," and they "decreased to a minimum during the Little Ice Age cooling (1650–1800 AD), before rising again to the modern atmospheric level of 550 ppt." Given that "today,

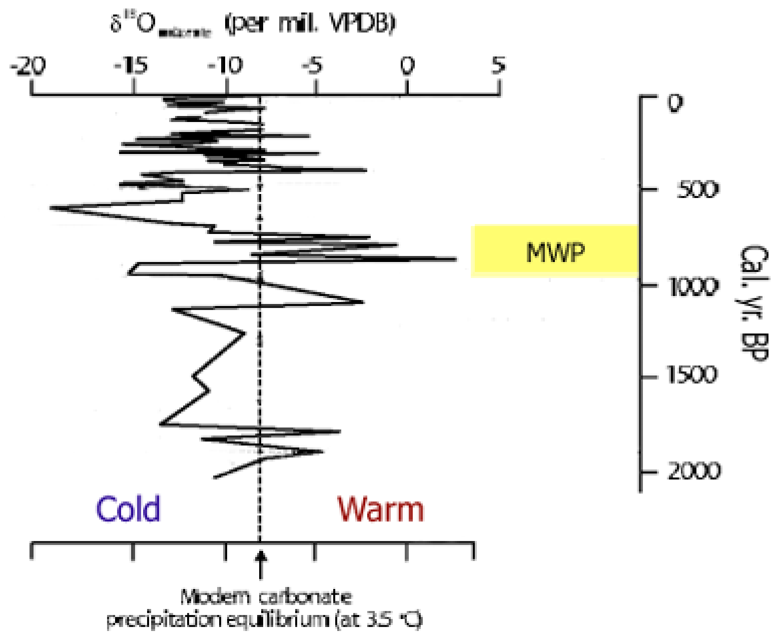

Figure 4.2.4.2.1.2. Sombre Lake $\delta^{18}O$ record showing the relative warmth of the MWP compared to the CWP. Adapted from Noon, P.E., Leng, M.J., and Jones, V.J. 2003. Oxygen-isotope ($\delta^{18}O$) evidence of Holocene hydrological changes at Signy Island, maritime Antarctica. *The Holocene* **13**: 251–263.

more than 90% of the CH_3Cl sources and the majority of CH_3Cl sinks lie between 30°N and 30°S (Khalil and Rasmussen, 1999; Yoshida *et al*., 2004)," they conclude "it is likely that climate-controlled variability in CH_3Cl reflects changes in tropical and subtropical conditions." They state, "ice core CH_3Cl variability over the last two millennia suggests a positive relationship between atmospheric CH_3Cl and global mean temperature."

As best as can be determined from the graphical representation of their data, the peak CH_3Cl concentration measured by Williams *et al*. during the MCA is approximately 533 ppt, which is within 3 percent of its current mean value of 550 ppt and well within the range of 520 to 580 ppt that characterizes methyl chloride's current variability. It therefore may be validly concluded the mean peak temperature of the MCA (Medieval Warm Period) over the latitude range 30°N to 30°S—and possibly over the entire globe—may not have been materially different from the mean peak temperature so far attained during the Current Warm Period.

Hall (2007) presented "radiocarbon and geomorphologic data that constrain [the] late-Holocene extent of the Collins Ice Cap on Fildes Peninsula (King George Island, South Shetland Islands: 62°10'51"S, 58°54'13"W)," which "yield information on times in the past when climate in the South Shetland Islands must have been as warm as or warmer than today," based on field mapping of moraines and glacial deposits adjacent to the ice cap as well as radiocarbon dates of associated organic materials. Such data, Hall writes, "indicate ice advance after ~650 cal. yr BP (AD ~1300)," which she notes is "broadly contemporaneous with the 'Little Ice Age', as defined in Europe." She also says this was "the only advance that extended beyond the present ice margin in the last 3500 years, making the Little Ice Age in that part of the world likely the coldest period of the current interglacial. And since "the present ice cap margin ... is still more extensive than it was prior to ~650 cal. yr BP" she concludes the climate prior to that time, which would have comprised the Medieval Warm Period, may have been "as warm as or warmer than present."

Working with an ice core (IND-22/B4) extracted during the austral summer of 2003 from the coastal region of Dronning Maud Land, East Antarctica (70°51.3'S, 11°32.2'E) as part of the 22nd Indian Antarctic Expedition, Thamban *et al*. (2011) developed 470-year histories of $\delta^{18}O$ and δD that "showed similar down core fluctuations with [an] excellent positive relationship (R^2 = 0.9; n = 216) between the two." Based on a $\delta^{18}O$ vs. surface air temperature (SAT) relationship developed for this region by Naik *et al*. (2001), they derived the regional temperature history depicted in Figure 4.2.4.2.1.3.

In describing the temperature history, the four Indian researchers state, "the estimated surface air temperature at the core site revealed a significant warming of 2.7°C with a warming of ~0.6°C per century for the past 470 years," not surprising given that the starting point for this record is the depth of the Little Ice Age. While the record shows decadal fluctuations, there has been no net warming for the entire twentieth century, with the warmest

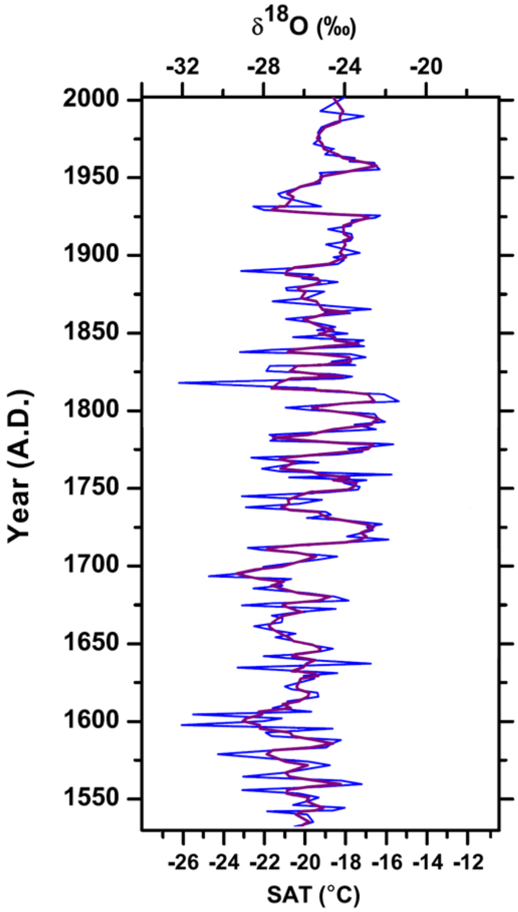

Figure 4.2.4.2.1.3. Surface air temperature (SAT) as derived from $\delta^{18}O$ data vs. time in years AD. Adapted from Thamban, M., Laluraj, C.M., Naik, S.S., and Chaturvedi, A. 2011. Reconstruction of Antarctic climate change using ice core proxy records from coastal Dronning Maud Land, East Antarctica. *Journal of the Geological Society of India* **78**: 19–29.

temperatures of the century occurring around 1925 and 1960.

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4.2.4.2.2 The Past One to Two Centuries

Another significant impediment to the CO_2-induced global warming hypothesis comes from the instrumental temperature record of the more recent past. According to nearly all climate models, CO_2-induced global warming should be most evident in Earth's polar regions, but analyses of Antarctic near-surface and tropospheric air temperature records tell a radically different story.

Doran *et al*. (2002) examined temperature trends in the McMurdo Dry Valleys of Antarctica over the period 1986 to 2000, reporting a cooling rate of approximately 0.7°C per decade. This dramatic rate of cooling "reflects longer term continental Antarctic cooling between 1966 and 2000." In addition, the 14-year temperature decline in the dry valleys occurred in the summer and autumn, as did most of the 35-year cooling over the continent as a whole exclusive of the dry valley data.

Comiso (2000) assembled and analyzed Antarctic temperature data from 21 surface stations and from infrared satellites operating since 1979, finding for all of Antarctica, temperatures declined by 0.08°C and 0.42°C per decade, respectively. Thompson and Solomon (2002) also report a cooling trend for the interior of Antarctica.

In spite of the decades-long cooling observed for the continent as a whole, one region of Antarctica has warmed over the same time period: the Antarctic Peninsula/Bellingshausen Sea region. But the temperature increase there is not evidence of CO_2-induced global warming.

According to Vaughan *et al*. (2001), "rapid regional warming" has led during the past 50 years to the loss of seven ice shelves, including the Prince Gustav Channel Ice Shelf, which collapsed in this region in 1995. However, they note sediment cores from 6,000 to 1,900 years ago suggest the Prince Gustav Channel Ice Shelf "was absent then and climate was as warm as it has been recently," although there was much less CO_2 in the air than there is today. Vaughan *et al*. say it "is superficial" to cite the twentieth century increase in atmospheric CO_2 concentration as the cause of the recent regional warming without providing an explanatory mechanism.

Thompson and Solomon (2002) suggest much of the warming can be explained by "a systematic bias toward the high-index polarity of the SAM," or Southern Hemispheric Annular Mode, such that the ring of westerly winds encircling Antarctica has recently been spending more time in its strong-wind phase. A similar conclusion was reached by Kwok and Comiso (2002), who report over the 17-year period 1982–1998 the SAM index shifted towards more positive values (0.22/decade). They also note a positive polarity of the SAM index "is associated with cold anomalies over most of Antarctica with the center of action over the East Antarctic plateau." At the same time, the Southern Oscillation (SO) index shifted in a negative direction, indicating "a drift toward a spatial pattern with warmer temperatures around the Antarctic Peninsula, and cooler temperatures over much of the continent."

Thus Kwok and Comiso conclude the positive trend in the coupled mode of variability of these two indices represents a "significant bias toward positive polarity." Also, the SAM "has been shown to be related to changes in the lower stratosphere (Thompson and Wallace, 2000)" and "the high index polarity of the SAM is associated with the trend toward a cooling and strengthening of the Southern Hemisphere stratospheric polar vortex during the stratosphere's relatively short active season in November," as Thompson and Solomon (2002) hypothesized.

Mulvaney *et al*. (2012) drilled an ice core to the bed of the ice cap on James Ross Island, which lies just off the northeastern tip of the Antarctic Peninsula, next to an area that has experienced a series of recent ice-shelf collapses. Based on deuterium/hydrogen isotope ratios of the ice (δD), they developed a temperature history of the region that spans the entire Holocene and extends into the last glacial period. They found "the Antarctic Peninsula experienced an early Holocene warm period followed by stable temperatures, from about 9200 to 2500 years ago, that were similar to modern-day levels." They also found "the high rate of warming over the past century is unusual (but not unprecedented) in the context of natural climate variability over the past two millennia." More specifically, they state, "over the past 100 years, the James Ross Island ice-core record shows that the mean temperature there has increased by 1.56 ± 0.42°C," which ranks as one of the fastest (upper 0.3%) warming trends since 2,000 years before present, according to a set of moving 100-year analyses that demonstrate "rapid recent warming of the Antarctic Peninsula is highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era." Although the temperature of the northern Antarctic Peninsula has risen at a rate of 2.6 ± 1.2°C over the past half-century, they state, "repeating the temperature trend analysis using 50-year windows confirms the finding that the rapidity of recent Antarctic Peninsula warming is unusual but not unprecedented."

Watkins and Simmonds (2000), who analyzed region-wide changes in sea ice, suggest Antarctica as a whole appears to be experiencing a cooling trend. Reporting on trends in several Southern Ocean sea ice parameters over the period 1987 to 1996, they found statistically significant increases in sea ice area and total sea ice extent, as well as an increase in sea ice season length since the 1990s. Combining these results with those from a previous study revealed the trends to be consistent back to at least 1978. And in another study of Antarctic sea ice extent, Yuan and Martinson (2000) report the net trend in the mean Antarctic ice edge over the past 18 years has been an equator-ward expansion of 0.011 degree of latitude per year.

Liu *et al*. (2004) used sea ice concentration data retrieved from the scanning multi-channel microwave radiometer on the Nimbus 7 satellite and the spatial sensor microwave/imager on several defense meteorological satellites to develop a quality-controlled history of Antarctic sea ice variability covering an entire 22-year solar cycle (1979–2002) that included different states of the Antarctic Oscillation and several ENSO events. They then evaluated total sea ice extent and area trends by means of linear least-squares regression. They report, "overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (~4,801 km^2/yr)." In addition, they determined "the total Antarctic sea ice area (the cumulative area of the ocean actually covered by at least 15% ice concentrations) has increased significantly by ~13,295 km^2/yr, exceeding the 95% confidence level," while noting "the upward trends in the total ice extent and area are robust for different cutoffs of 15, 20, and 30% ice concentrations (used to define the ice extent and area)."

Turner *et al*. (2005) used a "new and improved" set of Antarctic climate data, described in detail by Turner *et al*. (2004), to examine "the temporal variability and change in some of the key meteorological parameters at Antarctic stations." This revealed a warming at low elevations on the western coast of the Antarctic Peninsula, which they describe as being "as large as any increase observed on Earth over the last 50 years," and which at the Faraday (now Vernadsky) station was about 2.5°C. However, they note the "region of marked warming is quite limited and is restricted to an arc from the southwestern part of the peninsula, through Faraday to a little beyond the tip of the peninsula."

Outside the Antarctic Peninsula, they report "there has been a broad-scale change in the nature of the temperature trends between 1961–90 and 1971–2000." Specifically, of the ten coastal stations that have long enough records to allow 30-year temperature trends to be computed for both of these periods, "eight had a larger warming trend (or a smaller cooling trend) in the earlier period." Four changed from warming to cooling, as did the interior Vostok site, and at the South Pole the rate of cooling intensified by a factor of six. Thus, over the latter part of the twentieth century—during which the IPCC claims to have found the most dramatic global warming of the past two millennia—fully 80 percent of the Antarctic coastal stations with sufficiently long temperature records revealed either an intensification of cooling or a reduced rate of warming, while four coastal sites and one interior site shifted from warming to cooling. All of this occurred in one of the planet's high-latitude polar regions, where CO_2-induced global warming has been predicted to be more strongly expressed than any other place on the planet.

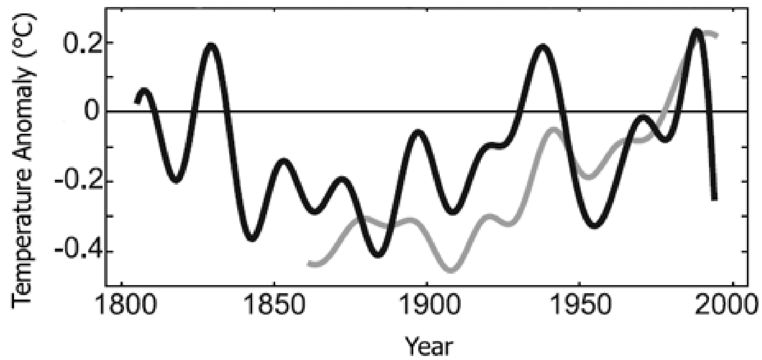

Figure 4.2.4.2.2.1. Mean temperature histories of Antarctica (dark line) and the Southern Hemisphere (lighter line), adapted from the paper of Schneider, D.P., Steig, E.J., van Ommen, T.D., Dixon, D.A., Mayewski, P.A., Jones, J.M., and Bitz, C.M. 2006. Antarctic temperatures over the past two centuries from ice cores. *Geophysical Research Letters* **33**: 10.1029/ 2006GL027057.

Schneider *et al*. (2006)_utilized 200 years of sub-annually resolved $\delta^{18}O$ and δD records from precisely dated ice cores obtained from Law Dome, Siple Station, Dronning Maud Land and two West Antarctic sites of the United States component of the International Trans-Antarctic Scientific Expedition to create a 200-year-long Antarctic temperature reconstruction representing the main part of the continent. The results of this undertaking, after application of a multi-decadal low-pass filter to the yearly data, are illustrated in Figure 4.2.4.2.2.1, along with the similarly treated data of the Southern Hemisphere instrumental temperature record, where the zero line represents the 1961–1990 climatological means of the two records.

Schneider *et al.* say "it is notable that the reconstructed Antarctic temperature record is in phase with the Southern Hemisphere mean instrumental record." This statement roughly describes the relationship between the two histories, but only until 1990, after which the Antarctic temperature history dramatically diverges from the Southern Hemisphere record. The seven scientists also state the Antarctic temperature reconstruction "provides evidence for long-term Antarctic warming," and if all the data they had were those that stretch from 1840 to 1990, they would be correct. However, when their "before and after" data are included, this statement is readily seen to be incorrect.

Schneider *et al*.'s data suggest there was nothing unusual, unnatural, or unprecedented about any Antarctic temperatures of any part of the twentieth century. Their data also demonstrate it was significantly colder in Antarctica near the end of the twentieth century than in the early decades of the nineteenth century, when the air's CO_2 concentration was about 100 ppm less than it is today, while data compiled by others indicates it may be even colder there today.

Chapman and Walsh (2007) used monthly surface air temperatures from manned and automatic weather stations along with ship/buoy observations from the high-latitude Southern Hemisphere to develop a gridded database with resolution appropriate for applications ranging from spatial trend analyses to climate change impact assessments. These data came from 460 locations in the Southern Hemisphere, where temperatures over land were obtained from 19 manned stations of the World Monthly Surface Station Climatology network, most of which were located in coastal areas of the Antarctic continent, plus 73 stations of the Automated Weather Station network, many of which were situated further inland. Temperatures over the sea were obtained from the International Comprehensive Ocean-Atmosphere Data repository. The two researchers used correlation length scaling "to enhance information content while limiting the spatial extent of influence of the sparse data in the Antarctic region."

The final results of Chapman and Walsh's efforts in this regard are presented in Figure 4.2.4.2.2.2. This figure clearly shows a post-1958 warming of Antarctica and much of the surrounding Southern

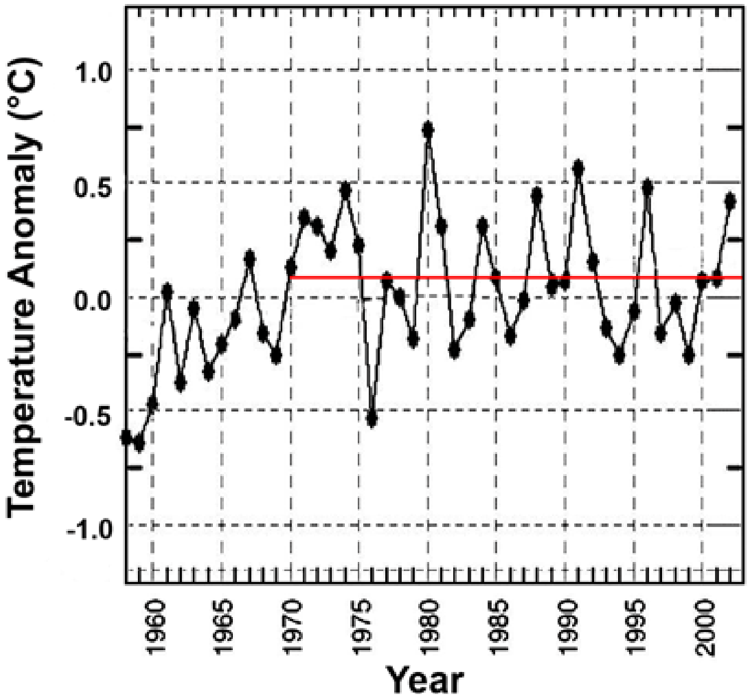

Figure 4.2.4.2.2.2. Annual surface air temperature anomalies relative to the 1958-2002 mean for the region of the Southern Hemisphere extending from 60 to 90°S. Adapted from Chapman, W.L. and Walsh, J.E. 2007. A synthesis of Antarctic temperatures. *Journal of Climate* **20**: 4096–4117.

Ocean. From approximately 1970 to the end of the record, however, temperatures of the region simply fluctuated around an anomaly mean of about 0.12°C, neither warming nor cooling. This is rather surprising in light of the fact that the region of study includes the Antarctic Peninsula, which experienced phenomenal warming during this period. Nevertheless, the mean surface air temperature of the entire region changed not at all, over a period of time that saw the air's CO_2 concentration rise by approximately 47 ppm, about 15 percent of its 1970 value, as per the Mauna Loa CO_2 record. Clearly, the continent of Antarctica, together with much of the Southern Ocean that surrounds it, has been unaffected by the warming supposedly produced by anthropogenic emissions of CO_2 and other greenhouse gases over the last three decades of the twentieth century.

Concentrating on the spring–summer period of November/December/January, Laine (2008) determined 1981–2000 trends of Antarctic ice-sheet and sea-ice surface albedo and temperature, as well as sea-ice concentration and extent, based on Advanced Very High Resolution Polar Pathfinder data in the case of ice-sheet surface albedo and temperature, and the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave Imagers in the case of sea-ice concentration and extent. These analyses were carried out for the continent as a whole and for five longitudinal sectors emanating from the South Pole: 20°E–90°E, 90°E–160°E, 160°E–130°W, 130°W–60°W, and 60°W–20°E.

Laine found "all the regions show negative spring–summer surface temperature trends for the study period" and "the slight cooling trends seem to be parallel with the results of Comiso (2000), who studied Antarctic temperature trends using both satellite and station data." In addition, the Finnish researcher states, "the sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero." Laine also reports "the Antarctic region as a whole and all the sectors separately show slightly positive spring–summer albedo trends."

Monaghan and Bromwich (2008) reviewed what has been learned about snowfall and near-surface air temperature over the past five decades in Antarctica. They point out, "snowfall is the largest contributor to the growth of the ice sheets, and near-surface temperature controls surface melting, which in turn has important impacts on the stability of Antarctic ice shelves and glaciers," which ultimately impact global sea level.

The two researchers from the Byrd Polar Research Center of Ohio State University (USA) first note "instrumental records indicate statistically insignificant seasonal and annual near-surface temperature changes over continental Antarctica from the late 1950s through 2000," citing the work of Turner *et al*. (2005). On the Antarctic Peninsula, by contrast, temperature measured at the Faraday/Vernadsky station rose at the phenomenal rate of 0.56°C per decade from 1951 to 2000. But the peninsula comprises a mere 4 percent of the continent's total surface area, and its warming, although dramatic, is only a small-scale anomaly.

In describing another study of the temperature history of Antarctica, Monaghan and Bromwich report, "Chapman and Walsh (2007) performed an objective analysis of Antarctic near-surface temperatures from the early 1950s through 2002 and found the overall Antarctic temperature trends depend on the period for which they are calculated, being positive prior to 1965 (through 2002), and mainly negative thereafter, although never statistically significant for any period." Similarly, after citing the work of Kwok and Comiso (2002) with skin temperature records derived from Advanced Very High Resolution Radiometer instrumentation flown aboard polar-orbiting satellites, the work of Schneider *et al*. (2006) with temperatures derived from ice-core stable isotopes, and the work of Monaghan *et al*. (2008) that blended the instrumental temperature record with model reanalysis temperature fields, Monaghan and Bromwich conclude, "overall there have not been statistically significant Antarctic near-surface temperature trends since the International Geophysical Year" of 1957–1958.

Turning their attention to snowfall, Monaghan and Bromwich note "atmospheric models have been the primary tool for assessing temporal variability," and they report the latest such studies of Antarctic snowfall "indicate that no statistically significant increase has occurred since ~1980," citing the analyses of Monaghan *et al*. (2006) and van de Berg *et al*. (2005), although there have been cyclical changes related to similar changes in temperature. When the two variations are compared on decadal time scales, it appears snowfall over Antarctica could rise by as much as 5 percent for each 1°C increase in temperature.

As to what the future might hold for Antarctic snowfall in a warming world, the two researchers state, "if global climate model projections of 2–3.5°C temperature increases over Antarctica by the end of this century are accurate"—which is highly debatable—"a ~10%–20% increase in snowfall might be expected if the 1960–2004 sensitivity relationship holds." They note "a 15% increase of Antarctic snowfall would mitigate an additional ~1 mm per year [rise] of global sea level in 2100 compared to today." Thus the rise in sea level predicted by the IPCC to occur this century appears to be highly unlikely, especially in light of Monaghan and Bromwich's ultimate observation that "a widespread signal of Antarctic climate change is not obvious over the past ~50 years."

Sinclair *et al*. (2012) write, "although the Antarctic ice sheet plays a pivotal role in the global ocean and atmospheric circulation systems and their response to warming climates, there are few long-term observations of surface temperature across the continent," which they say is "particularly true for areas pole-ward of the Antarctic Peninsula because of the sparsity of scientific bases and problems associated with satellite measurements of surface temperature (Mayewski *et al*., 2009)." Consequently, they assert there is a "pressing need for a better understanding of climate variability and the forcings that underlie these changes."

Thus Sinclair *et al*. studied isotope-temperature relationships at a site on the Whitehall Glacier in northern Victoria Land (72°54'S, 169°5'E) on a flat ice divide about 12 km from the nearest seasonally open water. Working with an ice core drilled to a depth of 105 meters there in 2006/2007, they developed a well-calibrated isotope-temperature relationship and used it to reconstruct annual temperatures, as well as summer (December–February) and cold season (April–September) temperatures, for the 125-year span of their data. Over the full length of their record, the three researchers state, they could find "no significant [temperature] trends between 1882 and 2006." Neither were there any significant trends in either summer or cold season temperatures since 1958. However, they report "a decrease in cold season temperatures of -1.59°C ± 0.84°C/decade at 90% confidence (p = 0.07) since 1979," and this cooling was "coincident with a positive trend in the southern annular mode, which is linked to stronger southerly winds and increased sea ice extent and duration in the western Ross Sea," which they say "is one of the few regions experiencing a significant positive trend in sea ice and a negative trend in sea surface temperatures," citing Comiso *et al*. (2011).

It is clear the temperature history of Antarctica provides no evidence for the CO_2-induced global warming hypothesis and in fact argues strongly against it.

And even if the Antarctic were to warm as a result of some natural or anthropogenic-induced change in Earth's climate, the consequences likely would not be grave. Both the number and diversity of penguin species (Smith *et al*., 1999; Sun *et al*., 2000) likely would improve, as would the size and number of the continent's only two vascular plant species (Xiong *et al*., 2000). The great ice sheets likely would survive, as not even a warming event as dramatic as 10°C is predicted to result in a net change in the East Antarctic Ice Sheet (Näslund *et al*., 2000), which suggests predictions of catastrophic coastal flooding due to melting from the world's polar ice sheets are off the mark.

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4.2.4.3 Arctic

The IPCC has long predicted CO_2-induced global warming—which they assert has accelerated significantly during the twentieth century and is unprecedented in the past millennium or more—should be greatly amplified in Earth's polar regions:

> Robust evidence for polar amplification in either one or both hemispheres has been found in climate model experiments of past and future climate change, paleo-climate data and recent instrumental temperature records (Second Order Draft of AR5, dated October 5, 2012, p. 5-14).

As shown in the subsections below, the IPCC's claim of "robust evidence" of amplified CO_2-induced warming in Earth's polar regions is patently false, having been invalidated time and again by real-world data. From the birth and death of ice ages to the decadal variations of modern-day weather patterns, studies of the Arctic's climate show the atmosphere's CO_2 concentration is not a major player in bringing about significant changes in Earth's climate. In the following sections, we present brief reviews of pertinent studies of glacial periods, the Holocene, and the past few decades.

<u>4.2.4.3.1 The Past Several Interglacial Cycles</u>

Beginning with the current interglacial or Holocene, Darby *et al*. (2001) developed a 10,000-year multi-parameter environmental record from a thick sequence of post-glacial sediments obtained from cores extracted from the upper continental slope off the Chukchi Sea Shelf in the Arctic Ocean. They uncovered evidence that revealed "previously unrecognized millennial-scale variability in Arctic Ocean circulation and climate," along with evidence suggesting "in the recent past, the western Arctic Ocean was much warmer than it is today." They state, "during the middle Holocene the August sea surface temperature fluctuated by 5°C and was 3–7°C warmer than it is today," and they report their data revealed "rapid and large (1–2°C) shifts in bottom water temperature." They conclude, "Holocene variability in the western Arctic is larger than any change observed in this area over the last century."

Miller *et al*. (2005) summarize the main characteristics of the glacial and climatic history of the Canadian Arctic's Baffin Island since the Last Glacial Maximum by presenting biotic and physical proxy climate data derived from six lacustrine sediment cores recovered from four sites on Baffin Island. The paleoenvironmental implications of the new data were combined with the findings of prior studies to develop a regional picture of climatic conditions during deglaciation, the subsequent Holocene thermal maximum, the onset of Neogolaciationm and its intensification in the late Holocene. This work revealed "glaciers throughout the Canadian Arctic show clear evidence of Little Ice Age expansion, persisting until the late 1800s, followed by variable recession over the past century." Wherever the Little Ice Age advance can be compared to earlier advances, they note, "the Little Ice Age is the most extensive Late Holocene advance" and "some glaciers remain at their Little Ice Age maximum." Because the Little Ice Age in the Canadian Arctic spawned the region's most extensive glacial advances of the entire Holocene, and because many of the resulting glaciers persisted into the late 1800s, with some remaining at their maximum Little Ice Age extensions, it is only to be expected the region would experience a significant warming as the planet recovers from this coldest phase of the Holocene, independent of the air's CO_2 concentration.

Frechette *et al*. (2006) employed radiocarbon and luminescence dating of macrofossils contained in sediment cores recovered from three mid-Arctic lakes on the Cumberland Peninsula of eastern Baffin Island in the Canadian Arctic to isolate and study the portions of the cores pertaining to the interglacial that preceded the Holocene, which occurred approximately 117,000–130,000 years ago. They reconstructed the past vegetation and climate of the region during this period based on pollen spectra derived from the cores. "In each core," they write, "last interglacial sediments yielded remarkably high pollen concentrations, and included far greater percentages of shrub (*Betula* and *Alnus*) pollen grains than did overlying Holocene sediments." Also, "from applications of both correspondence analysis regression and best modern analogue methodologies, we infer July air temperatures of the last interglacial to have been 4 to 5°C warmer than present on eastern Baffin Island," greater warmth than in any interval within the Holocene. They say their temperature reconstruction is "directly comparable to both earlier qualitative estimates (LIGA Members, 1991; Bennike and Bocher, 1994), as well as more recent quantifications from ice core (NGRIP Members, 2004) and pollen (Andreev *et al*., 2004) analyses."

In a companion study, Francis *et al*. (2006) analyzed midge remains found in cores recovered from two of the same Baffin Island lakes (Fog Lake and Brother of Fog Lake) for which Frechette *et al*. analyzed pollen spectra, reconstructing lake water temperatures and mean July air temperatures for the Holocene and the prior interglacial period. They write, "reconstructions at both [lake] sites indicate that summer temperatures during the last interglacial were higher than at any time in the Holocene, and 5 to 10°C higher than present."

The 25 authors of a major review paper (CAPE-Last Interglacial Project Members, 2006) present "quantitative estimates of circum-Arctic Last Interglaciation (LIG) summer air and sea-surface temperatures reconstructed from proxy records preserved in terrestrial and marine archives," including beach morphology, beetles, benthic foraminifera, chironomids, coccoliths, δD, $\delta^{18}O$, dinocysts, insects, invertebrates, Mg/Ca ratio, mollusks, nanofossils, needles, ostracodes, planktic foraminifera, plant microfossils, pollen, soils, spores, tephra, and treeline position. They report, "quantitative reconstructions of LIG summer temperatures suggest that much of the Arctic was 5°C warmer during the LIG than at present." With respect to the impacts of this warmth, they state Arctic summers of the LIG "were warm enough to melt all glaciers below 5 km elevation except the Greenland Ice Sheet, which was reduced by ca 20–50% (Cuffey and Marshall, 2000; Otto-Bliesner *et al*., 2006)." In addition, they note, "the margins of permanent Arctic Ocean sea ice retracted well into the Arctic Ocean basin and boreal forests advanced to the Arctic Ocean coast across vast regions of the Arctic currently occupied by tundra."

Clearly, if there is anything strange or unusual about current Arctic temperatures it is that they are so much lower than they were during the maximum warmth of the current interglacial and, even more so, the prior interglacial. If the Arctic behaves anything like the Antarctic in this regard, one can extend this comparison back in time through three more interglacials, all of which were also warmer than the current one (Petit *et al*., 1999; Augustin *et al*., 2004).

White *et al*. (2010) produced a comprehensive review of past climate change in Earth's north polar region. The nine researchers describe how "processes linked with continental drift have affected atmospheric circulation, ocean currents, and the composition of the atmosphere over tens of millions of years," and "a global cooling trend over the last 60 million years has altered conditions near sea level in the Arctic from ice-free year-round to completely ice covered." They also report, "variations in arctic insolation over tens of thousands of years in response to orbital forcing have caused regular cycles of warming and cooling that were roughly half the size of the continental-drift-linked changes," and, in turn, this glacial-interglacial cycling "was punctuated by abrupt millennial oscillations, which near the North Atlantic were roughly half as large as the glacial-interglacial cycles." They also note "the current interglacial, the Holocene, has been influenced by brief cooling events from single volcanic eruptions, slower but longer lasting changes from random fluctuations in the frequency of volcanic eruptions, from weak solar variability, and perhaps by other classes of events."

White *et al*. conclude "thus far, human influence does not stand out relative to other, natural causes of climate change." They say the data "clearly show" that "strong natural variability has been characteristic of the Arctic at all time scales considered" and "the human influence on rate and size of climate change thus far does not stand out strongly from other causes of climate change."

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4.2.4.3.2 The Past Few Centuries through the Past Few Millennia

The IPCC contends current temperatures are both unnatural and unprecedented, a result of global warming caused by anthropogenic CO_2 emissions, and they claim this “unnaturalness” is most strongly expressed in the world’s Arctic regions. This section investigates that claim in the context of the latter part of the current interglacial or Holocene, based on studies conducted in the Arctic.

The Arctic—which climate models suggest should be sensitive to greenhouse-gas-induced warming—is still not as warm as it was many centuries ago, especially during portions of the Medieval Warm Period, when there was much less CO_2 and methane in the air than there is today. This further suggests there is no compelling reason to conclude, as does the IPCC, that the twentieth century increase in the air’s CO_2 content (a 120ppm rise above what it was during the warmer Medieval Warm Period) was the cause of twentieth century warming, especially when it is claimed such warming should be most evident and earliest expressed in high northern latitudes, and in light of the millennial-scale climatic cycle that alternately brings the Earth relatively warmer and cooler century-scale conditions throughout both glacial and interglacial periods alike.

4.2.4.3.2.1 Canada

Moore *et al*. (2001) analyzed sediment cores extracted from Donard Lake, Baffin Island, Canada (~66.25°N, 62°W), to produce a 1,240-year record of mean summer temperature for this region that averaged 2.9°C over the period AD 750–1990 (see Figure 4.2.4.3.2.1.1). Within this period there were several anomalously warm decades with temperatures as high as 4°C around AD 1000 and 1100, and at the beginning of the thirteenth century Donard Lake

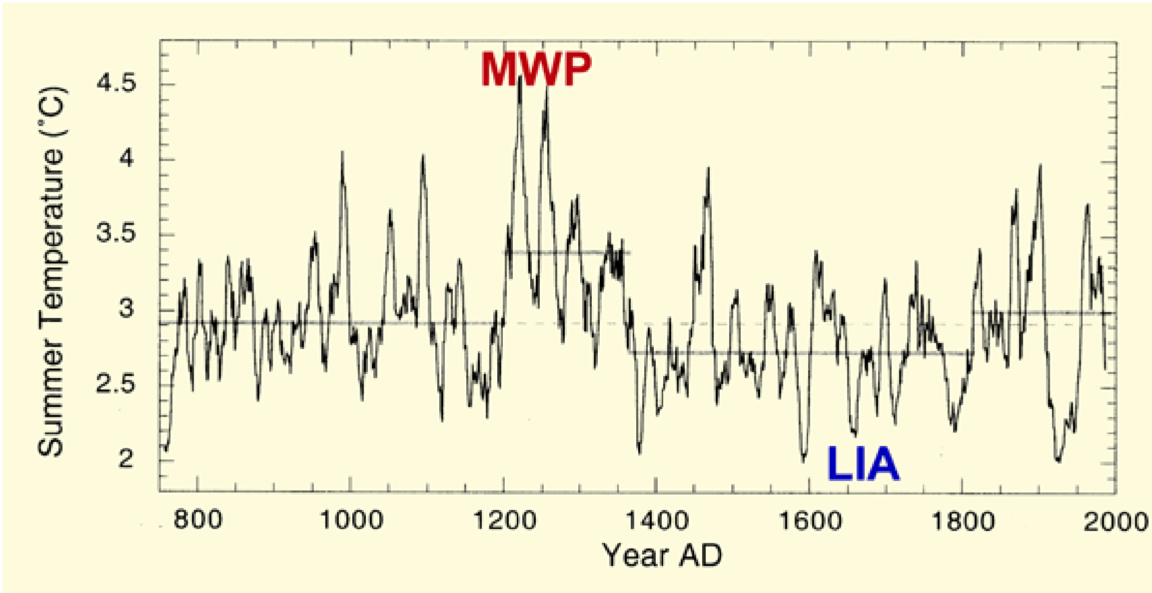

Figure 4.2.4.3.2.1.1. A 1,240-year proxy record of mean summer temperature from sediment cores extracted from Donard Lake, Baffin Island, Canada. Adapted from Moore, J.J., Hughen, K.A., Miller, G.H., and Overpeck, J.T. 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. *Journal of Paleolimnology* **25**: 503–517.

witnessed what Moore *et al.* called "one of the largest climatic transitions in over a millennium," as "average summer temperatures rose rapidly by nearly 2°C from AD 1195–1220, ending in the warmest decade in the record," with temperatures near 4.5°C. That temperature rise was followed by a period of extended warmth that lasted until an abrupt cooling event occurred around AD 1375, resulting in the following decade being one of the coldest in the record and signaling the onset of the Little Ice Age on Baffin Island, which lasted for 400 years.

At the modern end of the record, a gradual warming trend occurred over the period 1800–1900, followed by a dramatic cooling event that brought temperatures back down to levels characteristic of the Little Ice Age, which lasted until about 1950. Thereafter, temperatures rose once more throughout the 1950s and 1960s, whereupon they trended downward toward cooler conditions to the end of the record in 1990.

Kasper and Allard (2001) examined soil deformations caused by ice wedges, a widespread and abundant form of ground ice in permafrost regions that can grow during colder periods and deform and crack the soil. Working near Salluit, northern Quebéc (approx. 62°N, 75.75°W), they found evidence of ice wedge activity prior to AD 140, reflecting cold climatic conditions. Between AD 140 and 1030 this activity decreased, indicating warmer conditions. Trom AD 1030 to 1500 conditions cooled, and from 1500 to 1900 ice wedge activity was at its peak, when the Little Ice Age ruled, suggesting this climatic interval exhibited the coldest conditions of the past 4,000 years. Thereafter, a warmer period prevailed from about 1900 to 1946, followed by a return to cold conditions during the last five decades of the twentieth century, during which more than 90 percent of the ice wedges studied reactivated and grew by 20–30 cm, in harmony with a reported temperature decline of 1.1°C observed at the meteorological station in Salluit. This cooling is vastly different from the "unprecedented warming" the IPCC contends was occurring during this same period of time.

Besonen *et al*. (2008) derived thousand-year histories of varve thickness and sedimentation accumulation rate for Canada's Lower Murray Lake (81°20'N, 69°30'W), which is typically covered for about 11 months of each year by ice that reaches a thickness of 1.5 to 2 meters at the end of each winter. Citing seven other studies, they write, "field-work on other High Arctic lakes clearly indicates sediment transport and varve thickness are related to temperatures during the short summer season that prevails in this region, and we have no reason to think that this is not the case for Lower Murray Lake." The six scientists report the varve thickness and sediment accumulation rate histories of Lower Murray Lake reveal "the twelfth and thirteenth centuries were relatively warm" and often much warmer during this time period (AD 1080–1320) than at any point in the twentieth century.

Cook *et al*. (2009) examined sediment cores extracted from Lower Murray Lake in 2005 and 2006 to calculate annual mass accumulation rate (MAR) for the past five millennia, which they used to derive a relationship between MAR and July temperature at the two nearest permanent weather stations over the period of instrumental measurements. This revealed several periods over the past 5,000 years when the temperature of the region exceeded the peak temperature of the twentieth century, the most recent of which was during the Medieval Warm Period, delineated in Figure 4.2.4.3.2.1.2 as occurring between about AD 930 and 1400. The peak temperature of that period can be seen to have been about 0.6°C higher than the peak temperature of the Current Warm Period.

Vare *et al*. (2009) used a novel biomarker (IP25), which they describe as a mono-unsaturated highly branched isoprenoid synthesized by sea ice diatoms that have been shown to be stable in sediments below Arctic sea ice, together with "proxy data obtained from analysis of other organic biomarkers, stable isotope composition of bulk organic matter, benthic foraminifera, particle size distributions and ratios of inorganic elements," to develop a spring sea ice record for the central Canadian Arctic Archipelago. They discovered evidence for a decrease in spring sea ice between approximately 1,200 and 800 years before present (BP), which they associate with "the so-called Mediaeval Warm Period."

Fortin and Gajewski (2010) developed an 8,000-year history of mean July air temperature in the Wynniatt Bay region of Canada's Northern Victoria Island (72.29°N, 109.87°W) using two replicate sediment cores extracted from the central point of Lake WB02 in June 1997. They employed the modern analogue technique (MAT) and weighted averaging partial least squares (WAPLS) regression, utilizing chironomid species assemblage data. As best as can be determined from their graphical results, late-Holocene temperatures peaked about 1,100 years ago in both reconstructions, at values approximately 3.8°C warmer than the peak temperature of the Current Warm Period, which occurs at the end of their record in the AD 1990s in their MAT analysis, and approximately 1.0°C warmer than the peak temperature of the CWP, which also occurs at the end of their record in their WAPLS analysis.

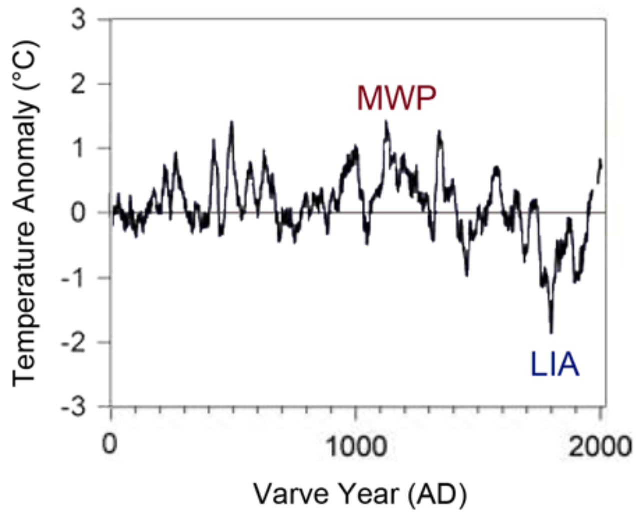

Figure 4.2.4.3.2.1.2. A proxy temperature reconstruction obtained from sediment cores extracted from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. Adapted from Cook, T.L., Bradley, R.S., Stoner, J.S., and Francus, P. 2009. Five thousand years of sediment transfer in a high arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. *Journal of Paleolimnology* **41**: 77–94.

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4.2.4.3.2.2 Greenland

For many millennia, the Arctic climate, like that of Earth as a whole, has both cooled and warmed independent of its atmospheric CO_2 concentration. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 concentration remained at values approximately 30 percent lower than today's. This subsection highlights studies that address the temperature history of Greenland.

Benthic foraminifera and lithofacies analyses were conducted by Jennings and Weiner (1996) on two marine sediment cores from Nansen Fjord, eastern Greenland (~68.25°N, 29.6°W) in an effort to infer changes in sea-ice conditions and water masses in the region since AD 730. The analyses revealed the presence of a Medieval Warm Period between about AD 730 and 1110, as depicted in Figure 4.2.4.3.2.2.1. The authors describe the climate during this time as "the warmest and most stable in the last millennium including the present day," in which sea ice in the fjord was "never or rarely" present in the summer.

Dahl-Jensen *et al.* (1998) used temperature measurements from two Greenland Ice Sheet boreholes to reconstruct the temperature history of this part of Earth over the past 50,000 years. Their data indicated that after the termination of the glacial period, temperatures steadily rose to a maximum of 2.5°C warmer than at present during the Holocene Climatic Optimum (4,000 to 7,000 years ago). The Medieval Warm Period (MWP) and Little Ice Age (LIA) also were observed in the record, with temperatures 1°C warmer and 0.5–0.7°C cooler than at the time of their writing, respectively. After the Little Ice Age, they report, temperatures once again rose, but they "decreased during the last decades," indicating the MWP in this part of the Arctic was significantly warmer than it was just before the turn of the century.

Wagner and Melles (2001) extracted a 3.5-m-long sediment core from a lake (Raffels So) on an island (Raffles O) located just off Liverpool Land on the east coast of Greenland, which they analyzed for several properties related to the past presence of seabirds there, obtaining a 10,000-year record that tells much about the region's climate history. Key to the study were biogeochemical data, which, in the words of the two researchers, reflect "variations in seabird breeding colonies in the catchment which influence nutrient and cadmium supply to the lake." These data revealed sharp increases in the values of the parameters they represented between about 1,100 and 700 years before present (BP), indicative of the summer presence of significant numbers of seabirds during that "medieval warm period," as Wagner and Melles describe it, which was preceded by a several-hundred-year period (the Dark Ages Cold Period) with little or no bird presence. After the Medieval

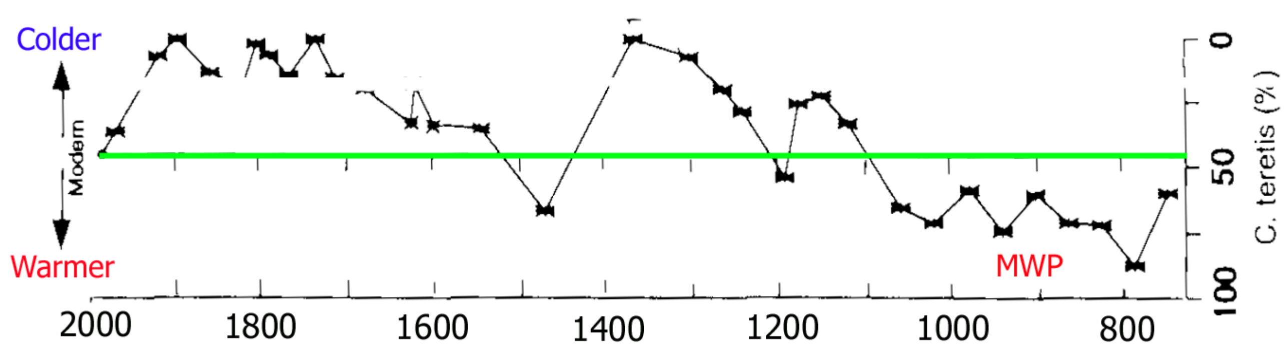

Figure 4.2.4.3.2.2.1. Percentage of Cassidulina teretis, an indicator of Atlantic Intermediate Water, in Nansen Fjord, Eastern Greenland. The horizontal green line indicates the modern percentage of C. teretis. Derivations below (above) this line indicate warmer (cooler) conditions. Adapted from Jennings, A.E. and Weiner, N.J. 1996. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. *The Holocene* **6**: 179–191.

Warm Period, their data suggest another absence of birds during what they call "a subsequent Little Ice Age," which they say was "the coldest period since the early Holocene in East Greenland."

The Raffels So data also show signs of a resettlement of seabirds during the last century, as indicated by an increase of organic matter in the lake sediment and confirmed by bird counts. Values of the most recent measurements of seabird numbers were not as great as those inferred for the earlier Medieval Warm Period, suggesting higher temperatures prevailed during much of the period from 1,100 to 700 years BP than those observed over the most recent hundred years.

Kaplan *et al*. (2002) derived a climate history of the Holocene by analyzing the physical-chemical properties of sediments obtained from a small lake in the southern sector of Greenland. The interval from 6,000 to 3,000 years BP was marked by warmth and stability, but the climate cooled thereafter until its culmination in the Little Ice Age. From 1300–900 years BP, there was a partial amelioration during the Medieval Warm Period, which was associated with an approximate 1.5°C rise in temperature.

Working on a floating platform in the middle of a small lake (Hjort So) on an 80-km-long by 10.5-km-wide island (Store Koldewey) just off the coast of Northeast Greenland, Wagner *et al*. (2008) recovered two sediment cores of 70 and 252 cm length, which they analyzed for grain-size distribution, macro-fossils, pollen, diatoms, total carbon, total organic carbon, and several other parameters. The sequences for those parameters were dated by accelerator mass spectrometry, with radiocarbon ages translated into calendar years before present. This revealed an "increase of the productivity-indicating proxies around 1,500–1,000 cal year BP, corresponding with the medieval warming," and "after the medieval warming, renewed cooling is reflected in decreasing amounts of total organic carbon, total diatom abundance, and other organisms, and a higher abundance of oligotrophic to meso-oligotrophic diatom taxa." They continue, "this period, the Little Ice Age, was the culmination of cool conditions during the Holocene and is documented in many other records from East and Northeast Greenland, before the onset of the recent warming [that] started ca. 150 years ago."

In addition to finding evidence for the Medieval Warm Period, the six researchers' statement that the Little Ice Age was the culmination, or most extreme subset, of cool conditions during the Holocene, suggests it would not be at all unusual for such a descent into extreme coolness to be followed by some extreme warming, which further suggests there is nothing unusual about the degree of subsequent warming experienced over the twentieth century.

Norgaard-Pedersen and Mikkelsen (2009) analyzed materials obtained from a sediment core retrieved in August 2006 from the deepest basin of Narsaq Sound in southern Greenland, inferring various "glacio-marine environmental and climatic changes" that had occurred over the prior 8,000 years. This work revealed the existence of two periods (2.3–1.5 ka and 1.2–0.8 ka) that appeared to coincide roughly with the Roman and Medieval Warm Periods. They identified the colder period that followed the Medieval Warm Period as the Little Ice Age and the colder period that preceded it as the Dark Ages Cold Period. Citing the work of Dahl-Jensen *et al*. (1998), Andresen *et al*. (2004), Jensen *et al*. (2004), and Lassen *et al*. (2004), the two Danish scientists say the cold and warm periods identified in those studies "appear to be more or less synchronous to the inferred cold and warm periods observed in the Narsaq Sound record," providing additional evidence for the reality of the naturally occurring phenomenon that governs this millennial-scale oscillation of climate.

Vinther *et al*. (2010) analyzed 20 ice core records from 14 sites, all of which stretched back at least 200 years, as well as near-surface air temperature data from 13 locations along the southern and western coasts of Greenland that covered approximately the same time interval (1784–2005), plus a similar temperature dataset from northwest Iceland, said by the authors to be employed "in order to have some data indicative of climate east of the Greenland ice sheet." This work demonstrated winter $\delta^{18}O$ was "the best proxy for Greenland temperatures." Based on that determination and working with three longer ice core $\delta^{18}O$ records (DYE-3, Crete and GRIP), they developed a temperature history that extended more than 1,400 years back in time.

This history revealed "temperatures during the warmest intervals of the Medieval Warm Period"—which they define as occurring some 900 to 1300 years ago—"were as warm as or slightly warmer than present day Greenland temperatures." Vinther *et al*. also acknowledge the independent "GRIP borehole temperature inversion suggests central Greenland temperatures are still somewhat below the high temperatures that existed during the Medieval Warm Period."

Kobashi *et al*. (2010) state, "in Greenland, oxygen isotopes of ice (Stuiver *et al*., 1995) have been extensively used as a temperature proxy, but the data are noisy and do not clearly show multi-centennial trends for the last 1,000 years in contrast to borehole temperature records that show a clear 'Little Ice Age' and 'Medieval Warm Period' (Dahl-Jensen *et al*., 1998)." They further note nitrogen (N) and argon (Ar) isotopic ratios—$^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$, respectively—can be used to construct a temperature record that "is not seasonally biased, and does not require any calibration to instrumental records, and resolves decadal to centennial temperature fluctuations.

They use this new approach to construct a history of the last thousand years of central Greenland surface air temperature, based on values of the isotopic ratios of nitrogen and argon previously derived by Kobashi *et al*. (2008) from air bubbles trapped in the GISP2 ice core that had been extracted from central Greenland, obtaining the result depicted in Figure 4.2.4.3.2.2.2.

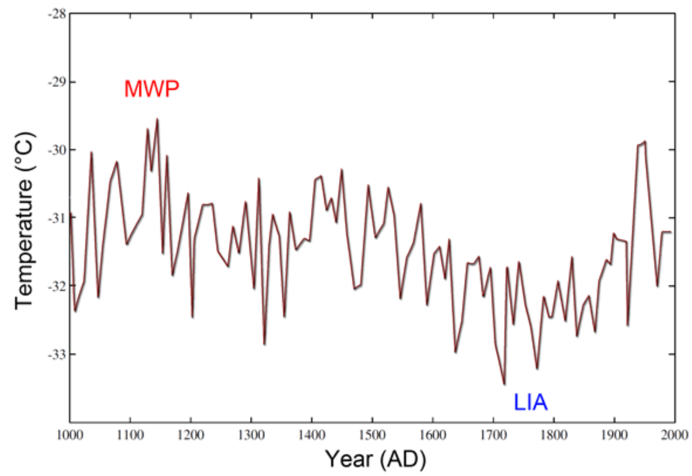

Figure 4.2.4.3.2.2.2. Central Greenland surface temperature reconstruction for the last millennium. Adapted from Kobashi, T., Severinghaus, J.P., Barnola, J.-M., Kawamura, K., Carter, T., and Nakaegawa, T. 2010. Persistent multi-decadal Greenland temperature fluctuation through the last millennium. *Climatic Change* **100**: 733–756.

This figure depicts the central Greenland surface temperature reconstruction produced by the six scientists. The peak temperature of the latter part of the Medieval Warm Period—which began some time prior to the start of their record, as demonstrated by the work of Dansgaard *et al*. (1975), Jennings and Weiner (1996), Johnsen *et al*. (2001), and Vinther *et al*. (2010)—appears to have been approximately 0.33°C greater than the peak temperature of the Current Warm Period and about 1.67°C greater than the temperature of the last decades of the twentieth century.

In a study based on the identification and quantification of various foraminiferal species found in a sediment core extracted from the bottom of a deep-water trough (Egedesminde Dyb) in the southwestern Disko Bugt of West Greenland at coordinates of ~68°38'N, 53°49'W, Perner *et al*. (2011) derived a 3,600-year proxy-temperature history of the West Greenland Current at that location. This history revealed "a marked long-term cooling trend over the last 3.6 ka BP," but superimposed on this longer-term cooling trend was evidence of millennial to centennial scale variability, where one of the warm intervals is said by them to constitute "the time period of the 'Medieval Climate Anomaly,'" which they identify as occurring over the period AD 1000–1500. Their proxy-temperature graph indicates the entire period was significantly warmer than the Current Warm Period has been to date.

Perner *et al*. (2013) identified and quantified the different types of benthic foraminiferal species found in two sediment cores beneath the path of the West Greenland Current (WGC) southwest of Disko Bugt (68°28.311'N, 54°00.119'W) on the West Greenland margin, determining the relative thermal history of the WGC over the past 7,300 years. This record revealed "(1) cooling at ~2.5 ka BP, linked to the 2.7 ka BP 'cooling event', (2) a warm phase centered at 1.8 ka BP, associated with the 'Roman Warm Period', (3) slight warming between 1.4 and 0.9 ka BP, linked to the 'Medieval Climate Anomaly' [MCA], (4) severe cooling of the WGC after 0.9 ka BP, culminating at 0.3 ka BP during the 'Little Ice Age.'" As to the degree of warmth of the MCA, the authors state, "our data show that oceanographic conditions (WGC) are relatively cool and remained cooler during the last 100 years than during the MCA," indicating the warmth of the Current Warm Period has not reached that experienced during the MCA.

Axford *et al*. (2013) examined sedimentary records from five lakes (North, Fishtote, Loon, Iceboom, and Pluto) near Jakobshavn Isbrae in central West Greenland to investigate the timing and magnitude of major Holocene climate changes, with their primary objective being "to constrain the timing and magnitude of maximum warmth during the early to middle Holocene positive anomaly in summer insolation." They did this by analyzing various properties of sediment cores extracted from the lakes in the summers of 2008 and 2009.

They write, "Based upon chironomid assemblages at North Lake, and supported by records of organic sedimentation in all five study lakes, we infer warmer-than-present temperatures by at least 7.1 ka [thousands of years before present] and Holocene maximum warmth between 6 and 4 ka," when they indicate "the local ice sheet margin was at its most retracted Holocene position" and "summer temperatures were 2–3°C warmer than present during that time of minimum ice sheet extent." A graphical representation of this temperature history is presented in Figure 4.2.4.3.2.2.3, with the concomitant history of Earth's atmospheric CO_2 concentration.

As illustrated in the figure, there is no relationship between the Holocene temperature history derived by Axford *et al*. and the air's CO_2 content. Over the first 1,800 years of the record, when the atmosphere's CO_2 concentration rose by just 10 ppm, Holocene temperatures rose, in the mean, by about 2.3°C. Then, over the following 2,400 years, when the air's CO_2 content rose by about 20 ppm, mean summer air temperatures dropped by approximately 2.6°C. And over the next 1,900 years, when the air's CO_2 content rose by 10 to 15 ppm,

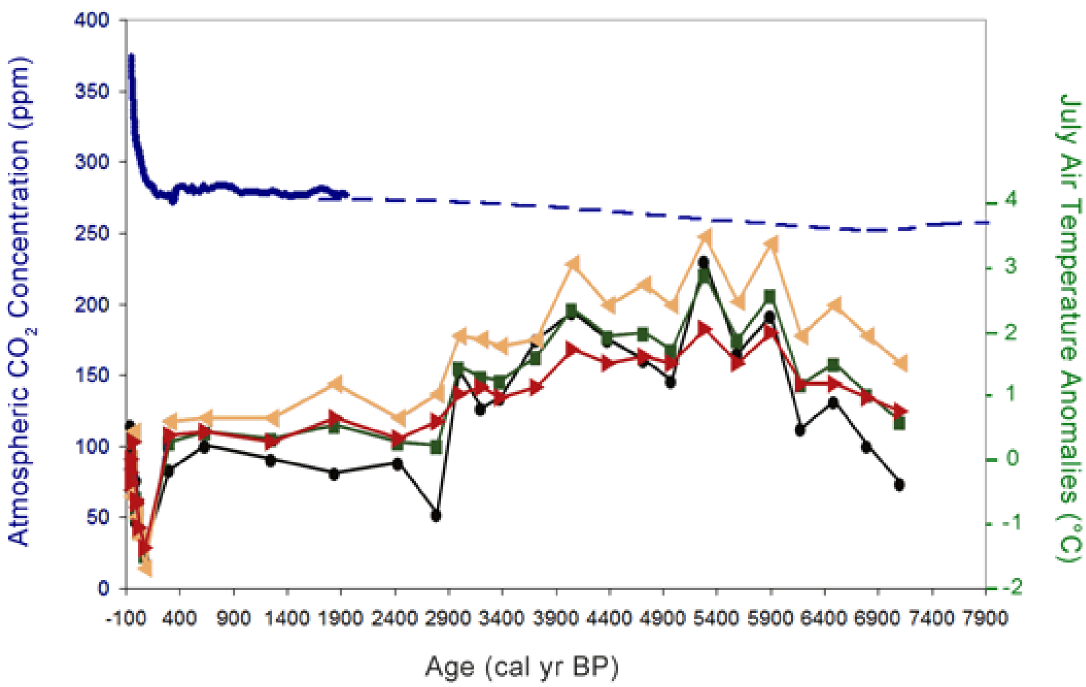

Figure 4.2.4.3.2.2.3. Reconstructed July air temperature anomalies in the vicinity of North Lake, inferred from chironomid data using three different calibration formulas: (1) Weighted-averaging, orange line with triangle data points, (2) Weighted-averaging with tolerance downweighting, red line with triangle data points, (3) Weighted-averaging partial-least-squares, black line with circle data points), plus the mean of the three sets of results (green line, square data points), as adapted from Axford, Y., Losee, S., Briner, J.P., Francis, D.R., Langdon, P.G., and Walker, I.R. 2013. Holocene temperature history at the western Greenland Ice Sheet margin reconstructed from lake sediments. *Quaternary Science Reviews* **59**: 87–100. Also shown is the concomitant history of Earth's atmospheric CO_2 concentration, as obtained from atmospheric measurements carried out at Mauna Loa, Hawaii (Boden, T.A., Kaiser, D.P., Sepanski, R.J., and Stoss, F.W. (Eds.) 1994. *Trends '93: A Compendium of Data on Global Change*. ORNL/CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee), together with ice core data obtained at Law Dome (Etheridge, D.M., Steele, L.P., Langenfelds, R.L, Francey, R.J., Barnola, J.-M., and Morgan, V.I. 1998. Historical CO_2 records from the Law Dome DE08, DE08-2, and DSS ice cores. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.) and Vostock, Antarctica (Keeling, C.D. and Whorf, T.P. 1998. Atmospheric CO_2 concentrations—Mauna Loa Observatory, Hawaii, 1958–1997 (revised August 1998). NDP-001. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee).

mean air temperature did not change. But over the final 300 or so years, when the atmospheric CO_2 concentration rose by 125 ppm, summer air temperatures first declined by about 1.9°C and then rose by about 1.9°C, for essentially no net change. The CO_2 concentration of Earth's atmosphere shows no consistent impact on July air temperatures in the vicinity of North Lake, Greenland, over the past seven millennia.

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4.2.4.3.2.3 Russia/Asian Arctic

Naurzbaev and Vaganov (2000) developed a 2,200-year temperature history using tree-ring data obtained from 118 trees near the upper-timberline in Siberia for the period 212 BC to AD 1996, as well as a similar history covering the period of the Holocene Climatic Optimum (3300 to 2600 BC). They compared their results with those obtained from an analysis of isotopic oxygen data extracted from a Greenland ice core. Fluctuations in average annual temperature derived from the Siberian record agreed well with air temperature variations reconstructed from the Greenland data, suggesting “the tree ring chronology of [the Siberian] region can be used to analyze both regional peculiarities and global temperature variations in the Northern Hemisphere.”

Naurzbaev and Vaganov report several warm and cool periods prevailed for several multi-century periods throughout the last two millennia: a cool period in the first two centuries AD, a warm period from AD 200 to 600, cooling again from 600 to 800 AD, followed by the Medieval Warm Period from about AD 850 to 1150, the cooling of the Little Ice Age from AD 1200 through 1800, followed by the recovery warming of the twentieth century. The latter temperature rise was “not extraordinary,” they write, and “the warming at the border of the first and second millennia [AD 1000] was longer in time and similar in amplitude.” In addition, their reconstructed temperatures for the Holocene Climatic Optimum reveal there was an even warmer period about 5,000 years ago, when temperatures averaged 3.3°C more than over the past two millennia.

Vaganov *et al*. (2000) also used tree-ring width as a temperature proxy, reporting temperature variations for the Asian subarctic region over the past 600 years. Their graph of these data reveals temperatures in this region exhibited a small positive trend from the beginning of the record until about AD 1750. Thereafter, a severe cooling trend ensued, followed by a 130-year warming trend from about 1820 through 1950, after which temperatures fell once again. Vaganov *et al*. determined the amplitude of twentieth century warming “does not go beyond the limits of reconstructed natural temperature fluctuations in the Holocene subarctic zone.” They further report finding a significant correlation with solar radiation and volcanic activity over the entire 600-year period (r = 0.32 for solar radiation, r = -0.41 for volcanic activity), which improved over the shorter interval (1800–1990) of the industrial period (r = 0.68 for solar radiation, r = -0.59 for volcanic activity).

Naurzbaev *et al*. (2002) developed a 2,427-year proxy temperature history for the part of the Taimyr Peninsula, northern Russia, lying between 70°30’ and 72°28’ North latitude, based on a study of ring-widths of living and preserved larch trees, noting it has been shown “the main driver of tree-ring variability at the polar timber-line [where they worked] is temperature (Vaganov *et al*., 1996; Briffa *et al*., 1998; Schweingruber and Briffa, 1996).” They found “the warmest periods over the last two millennia in this region were clearly in the third [Roman Warm Period], tenth to twelfth [Medieval Warm Period] and during the twentieth [Current Warm Period] centuries.” With respect to the second of these three periods, they emphasize “the warmth of the two centuries AD 1058–1157 and 950–1049 attests to the reality of relative mediaeval warmth in this region.” Their data also reveal the Roman and Medieval Warm Periods were warmer than the Current Warm Period has been to date; the beginning of the end of the Little Ice Age was somewhere in the vicinity of 1830; and the Current Warm Period peaked somewhere around 1940.

All of these observations are at odds with what is portrayed in the Northern Hemispheric hockey stick temperature history of Mann *et al*. (1998, 1999) and its thousand-year global extension developed by Mann and Jones (2003), in which the Current Warm Period is depicted as the warmest such era of the past two millennia, recovery from the Little Ice Age does not begin until after 1910, and the Current Warm Period experiences its highest temperatures in the latter part of the twentieth century’s final decade.

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4.2.4.3.2.4 Scandinavia and Iceland

Jiang *et al*. (2002) analyzed diatom assemblages from a high-resolution core extracted from the seabed of the north Icelandic shelf, which led to their reconstruction of a 4,600-year history of summer sea surface temperature at that location. Starting from a maximum value of about 8.1°C at 4,400 years BP, the climate was found to have cooled fitfully for about 1,700 years and then more consistently over the final 2,700 years of the record. The most dramatic departure from this long-term decline was centered on about 850 years BP, during the Medieval Warm Period, when the temperature rose by more than 1°C above the line describing the long-term downward trend to effect an almost complete recovery from the colder temperatures of the Dark Ages Cold Period, after which temperatures continued their descent into the Little Ice Age, ending with a final most recent value of approximately 6.3°C. Their data clearly show the Medieval Warm Period in this part of the Arctic was significantly warmer than it is there now.

Grudd *et al*. (2002) assembled tree-ring widths from 880 living, dead, and subfossil northern Swedish pines into a continuous and precisely dated chronology covering the period 5407 BC to AD 1997. The strong association between these data and summer (June–August) mean temperatures of the last 129 years of the period enabled them to produce a 7,400-year history of summer mean temperature for northern Swedish Lapland.

The most dependable portion of this record, based on the number of trees that were sampled, consisted of the last two millennia, which Grudd *et al*. say "display features of century-timescale climatic variation known from other proxy and historical sources, including a warm 'Roman' period in the first centuries AD and a generally cold 'Dark Ages' climate from about AD 500 to about AD 900." They also note "the warm period around AD 1000 may correspond to a so-called 'Mediaeval Warm Period,' known from a variety of historical sources and other proxy records." They state, "the climatic deterioration in the twelfth century can be regarded as the starting point of a prolonged cold period that continued to the first decade of the twentieth century," and this "Little Ice Age," in their words, is also "known from instrumental, historical and proxy records." Going back even further in time, the tree-ring record displays several more of these relatively warmer and colder periods. They report "the relatively warm conditions of the late twentieth century do not exceed those reconstructed for several earlier time intervals."

Seppa and Birks (2002) used a recently developed pollen-climate reconstruction model and a new pollen stratigraphy from Toskaljavri, a tree-line lake in the continental sector of northern Fennoscandia located just above 69°N latitude, to derive quantitative estimates of annual precipitation and July mean temperature. Their reconstructions "agree with the traditional concept of a 'Medieval Warm Period' (MWP) and 'Little Ice Age' in the North Atlantic region (Dansgaard *et al*., 1975) and in northern Fennoscandia (Korhola *et al*., 2000)." In addition, they report there was "a clear correlation between [their] MWP reconstruction and several records from Greenland ice cores," and "comparisons of a smoothed July temperature record from Toskaljavri with measured borehole temperatures of the GRIP and Dye 3 ice cores (Dahl-Jensen *et al*., 1998) and the $\delta^{18}O$ record from the Crete ice core (Dansgaard *et al*., 1975) show the strong similarity in timing of the MWP between the records." They also note, "July temperature values during the Medieval Warm Period (ca. 1400–1000 cal yr B.P.) were ca. 0.8°C higher than at present," where present means the last six decades of the twentieth century.

Isaksson *et al*. (2003) retrieved two ice cores (one from Lomonosovfonna and one from Austfonna) far above the Arctic Circle in Svalbard, Norway, after which the 12 scientists from Norway, Finland, Sweden, Canada, Japan, Estonia, and the Netherlands used $\delta^{18}O$ data to reconstruct a 600-year temperature history of the region. As would be expected in light of Earth's transition from the Little Ice Age to the Current Warm Period, the scientists report "the $\delta^{18}O$ data from both Lomonosovfonna and Austfonna ice cores suggest that the 20th century was the warmest during at least the past 600 years." However, the warmest decade of the twentieth century was centered on approximately 1930, and the instrumental temperature record at Longyearbyen also shows the decade of the 1930s to have been the warmest. The authors note, "as on Svalbard, the 1930s were the warmest decade in the Trondheim record." There was no net warming over the last seven decades of the twentieth century in the parts of Norway cited in this study.

Knudsen *et al*. (2004) documented climate changes over the past 1,200 years via high-resolution multi-proxy studies of benthic and planktonic foraminiferal assemblages, stable isotopes, and ice-rafted debris found in three sediment cores retrieved from the North Icelandic shelf. They learned "the time period between 1200 and around 7–800 cal. (years) BP, including the Medieval Warm Period, was characterized by relatively high bottom and surface water temperatures," after which "a general temperature decrease in the area marks the transition to ... the Little Ice Age." They also found "minimum sea-surface temperatures were reached at around 350 cal. BP, when very cold conditions were indicated by several proxies." Thereafter, they report, "a modern warming of surface waters ... is not registered in the proxy data" and "there is no clear indication of warming of water masses in the area during the last decades," even in sea surface temperatures measured over the period 1948–2002.

Bradwell *et al*. (2006) examined the link between late Holocene fluctuations of Lambatungnajokull (an outlet glacier of the Vatnajokull ice cap of southeast Iceland) and variations in climate, using geomorphological evidence to reconstruct patterns of past glacier fluctuations and lichenometry and tephrostratigraphy to date glacial landforms created by the glacier over the past four centuries. This work revealed "a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat" and "between 1930 and 1950 this relationship is striking." They also report, "ice-front recession was greatest during the 1930s and 1940s, when retreat averaged 20 m per year." Thereafter, the retreat "slowed in the 1960s" and "there has been little overall retreat since the 1980s."

The researchers also report, "the 20th-century record of reconstructed glacier-front fluctuations at Lambatungnajokull compares well with those of other similar-sized, non-surging, outlets of southern Vatnajokull," including Skaftafellsjokull, Fjallsjokull, Skalafellsjokull, and Flaajokull. They find "the pattern of glacier fluctuations of Lambatungnajokull over the past 200 years reflects the climatic changes that have occurred in southeast Iceland and the wider region."

Bradwell *et al*.'s findings indicate twentieth century summer air temperature in southeast Iceland and the wider region peaked in the 1930s and 1940s, and this warming was followed by a cooling that persisted through the end of the century. This history is about as different as can be imagined from the claim the warming of the globe over the last two decades of the twentieth century was unprecedented over the past two millennia, and this is especially significant for a high-northern-latitude region, where the IPCC claims CO_2-induced global warming should be earliest and most strongly expressed.

Grinsted *et al*. (2006) developed "a model of chemical fractionation in ice based on differing elution rates for pairs of ions ... as a proxy for summer melt (1130–1990)," based on data obtained from a 121-meter-long ice core they extracted from the highest ice field in Svalbard (Lomonosovfonna: 78°51'53"N, 17°25'30"E), which was "validated against twentieth-century instrumental records and longer historical climate proxies." This history shows, as illustrated in Figure 4.2.4.3.2.4.1, "in the oldest part of the core (1130–1200), the washout indices [were] more than 4 times as high as those seen during the last century, indicating a high degree of runoff." In addition, regular snow pit studies conducted near

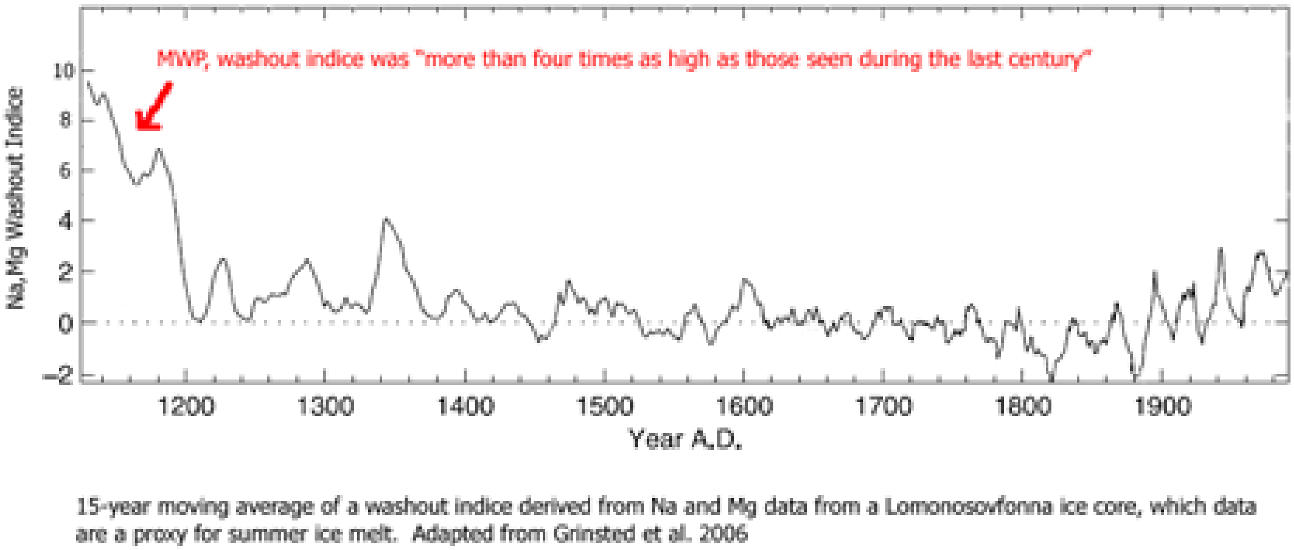

Figure 4.2.4.3.2.4.1. Fifteen-year moving average of a washout indice derived from Na and Mg data from a Lomonosovfonna ice core on Svalbard, which data are a proxy for summer ice melt. Adapted from Grinsted, A., Moore, J.C., Pohjola, V., Martma, T., and Isaksson, E. 2006. Svalbard summer melting, continentality, and sea ice extent from the Lomonosovfonna ice core. *Journal of Geophysical Research* **111**: 10.1029/2005JD006494..

the ice core site since 1997 (Virkkunen, 2004) found "the very warm 2001 summer resulted in similar loss of ions and washout ratios as the earliest part of the core." Grinsted *et al*. state, "this suggests that the Medieval Warm Period in Svalbard summer conditions [was] as warm (or warmer) as present-day, consistent with the Northern Hemisphere temperature reconstruction of Moberg *et al*. (2005)." In addition, they conclude "the degree of summer melt was significantly larger during the period 1130–1300 than in the 1990s," which suggests a large portion of the Medieval Warm Period was significantly warmer than the peak warmth of the Current Warm Period.

Noting the varve thicknesses of annually laminated sediments laid down by Hvitarvatn, a proglacial lake in the central highlands of Iceland, is controlled by the rate of glacial erosion and efficiency of subglacial discharge from the adjacent Langjokull ice cap, Larsen *et al*. (2011) employed a suite of environmental proxies contained in those sediments to reconstruct the region's climate variability and glacial activity over the past 3,000 years. These proxies included varve thickness, varve thickness variance, ice-rafted debris, total organic carbon (mass flux and bulk concentration), and the C:N ratio of sedimentary organic matter. The scientists found "all proxy data reflect a shift toward increased glacial erosion and landscape destabilization from ca 550 AD to ca 900 AD and from ca 1250 AD to ca 1950 AD, separated by an interval of relatively mild conditions." They note, "the timing of these intervals coincides with the well-documented periods of climate change commonly known as the Dark Ages Cold Period, the Medieval Warm Period, and the Little Ice Age."

In the case of the Medieval Warm Period, they note, "varve thickness decreases after 950 AD and remains consistently low through Medieval time with slightly thinner annual laminations than for any other multi-centennial period in the past 3000 years," which suggests the MWP was the warmest period of the past three millennia. They state, "the LIA was the most severe multi-centennial cold interval of the late Holocene" and "likely since regional deglaciation 10,000 years ago."

The 12 researchers of Esper *et al*. (2012), from Finland, Germany, Scotland, and Switzerland, write, "solar insolation changes, resulting from long-term oscillations of orbital configurations (Milankovitch, 1941), are an important driver of Holocene climate," referencing the studies of Mayewski *et al*. (2004) and Wanner *et al*. (2008). They note this forcing has been "substantial over the past 2000 years, up to four times as large as the 1.6 Wm^{-2} net anthropogenic forcing since 1750," as suggested by the work of Berger and Loutre (1991). On the basis of "numerous high-latitude proxy records," they note "slow orbital changes have recently been shown to gradually force boreal summer temperature cooling over the common era," citing Kaufman *et al*. (2009).

Esper *et al*. (2012) developed "a 2000-year summer temperature reconstruction based on 587 high-precision maximum latewood density (MXD) series from northern Scandinavia," accomplished "over three years using living and subfossil pine (*Pinus sylvestris*) trees from 14 lakes and 3 lakeshore sites above 65°N, making it not only longer but also much better replicated than any existing MXD time series." After calibrating the pine MXD series against regional June–July–August mean temperature over the period 1876–2006, they obtained their final summer temperature history for the period stretching from 138 BC to AD 2006, as depicted in Figure 4.2.4.3.2.4.2.

Esper *et al*. calculate a long-term cooling trend of -0.31 ± 0.03°C per thousand years, which they say is "missing in published tree-ring proxy records" but is "in line with coupled general circulation models (Zorita *et al*., 2005; Fischer and Jungclaus, 2011)." These computational results portray, as they describe it, substantial summer cooling over the past two millennia in northern boreal and Arctic latitudes.

"These findings," the researchers continue, "together with the missing orbital signature in published dendrochronological records, suggest that large-scale near-surface air temperature reconstructions (Mann *et al*., 1999; Esper *et al*., 2002; Frank *et al*., 2007; Hegerl *et al*., 2007; Mann *et al*., 2008) relying on tree-ring data may underestimate pre-instrumental temperatures including warmth during Medieval and Roman times," although they suggest the impacts of the omitted long-term trend in basic tree-ring data may "diminish towards lower Northern Hemisphere latitudes, as the forcing and radiative feedbacks decrease towards equatorial regions."

Why was much of the CO_2-starved world of Medieval and Roman times decidedly warmer (by about 0.3 and 0.5°C, respectively) than during the peak warmth of the twentieth century? If the greenhouse effect of atmospheric CO_2 has not been grossly overestimated, then it must currently be significantly tempered by some unappreciated negative-feedback phenomenon such that the basic greenhouse effect of Earth's rising atmospheric CO_2 concentration cannot fully compensate for the

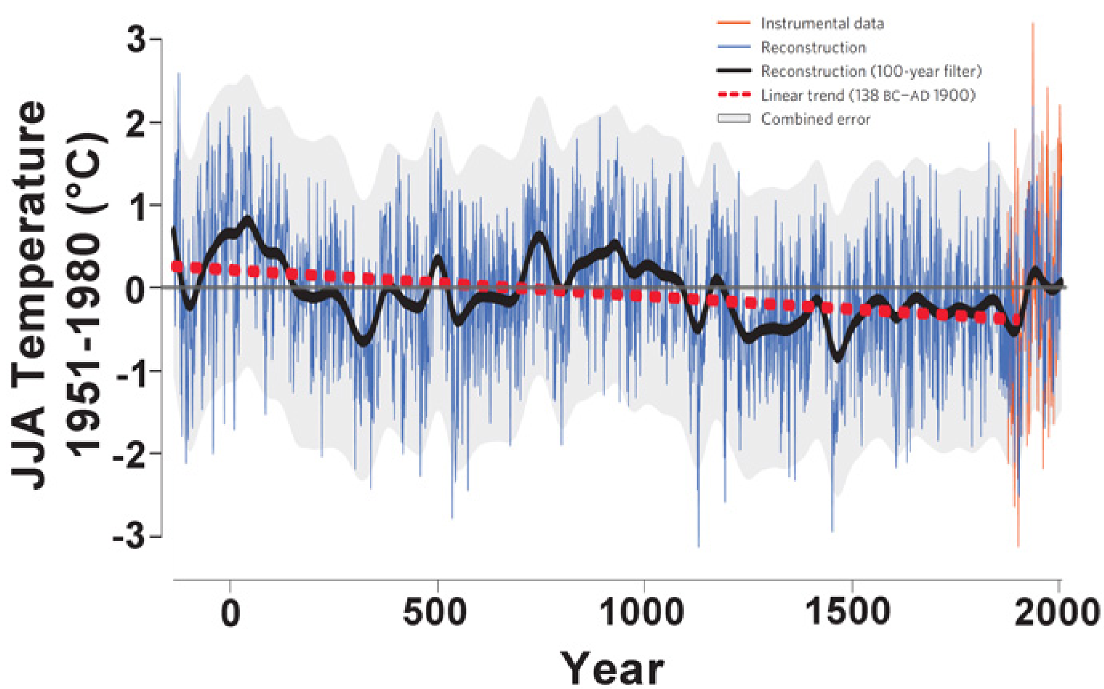

Figure 4.2.4.3.2.4.2. The summer (June–July–August) temperature reconstruction of Esper *et al*. (2012), adapted from Esper, J., Frank, D.C., Timonen, M., Zorita, E., Wilson, R.J.S., Luterbacher, J., Holzkamper S., Fischer, N., Wagner, S., Nievergelt, D., Verstege, A., and Buntgen, U. 2012. Orbital forcing of tree-ring data. *Nature Climate Change*: DOI 10.1038/NCLIMATE1589.

decrease in solar insolation experienced over the past two millennia as a result of the "long-term oscillations of orbital configurations" cited by Esper *et al*. (2012).

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4.2.4.3.2.5 The Rest of the Arctic

Overpeck *et al*. (1997) combined paleoclimatic records obtained from lake and marine sediments, trees, and glaciers to develop a 400-year history of circum-Arctic surface air temperature. From this record they determined the most dramatic warming of the last four centuries of the past millennium (1.5°C) occurred between 1840 and 1955, over which period the air's CO_2 concentration rose by 28 ppm, from approximately 285 ppm to 313 ppm. From 1955 to the end of the record (about 1990), the mean circum-Arctic air temperature declined by 0.4°C, while the air's CO_2 concentration rose by 41 ppm, from 313 ppm to 354 ppm.

Thus, over the first 115 years of Overpeck *et al*.'s record, as the air's CO_2 concentration rose by an average of 0.24 ppm/year, air temperature rose by an average of 0.013°C/year. Over the final 35 years of the record, when the air's CO_2 content rose at a mean rate of 1.17 ppm/year (nearly five times as fast), the rate-of-rise of surface air temperature *decelerated*, to a mean value (0.011°C/year), just the opposite of what one would have expected on the basis of greenhouse gas-induced warming theory.

Benner *et al*. (2004) noted, "thawing of the permafrost which underlies a substantial fraction of the Arctic could accelerate carbon losses from soils (Goulden *et al*., 1998)." In addition, "freshwater discharge to the Arctic Ocean is expected to increase with increasing temperatures (Peterson *et al*., 2002), potentially resulting in greater riverine export of terrigenous organic carbon to the ocean." And since the organic carbon in Arctic soils "is typically old, with average radiocarbon ages ranging from centuries to millennia (Schell, 1983; Schirrmeister *et al*., 2002)," they set about to measure the age of dissolved organic carbon (DOC) in Arctic rivers to determine whether increasing amounts of older carbon were being transported to the ocean, which would indicate enhanced regional warming.

The researchers sampled two of the largest Eurasian rivers, the Yenisey and Ob', which drain vast areas of boreal forest and extensive peat bogs, accounting for about a third of all riverine DOC discharge to the Arctic Ocean, as well as two much smaller rivers on the north slope of Alaska, the Ikpikpuk and Kokolik, whose watersheds are dominated by Arctic tundra. They found modern radiocarbon ages for all samples taken from all rivers, which indicate, they write, Arctic riverine DOC "is derived primarily from recently fixed plant litter and near-surface soil horizons." Because warming should have caused the average radiocarbon age of the DOC of Arctic rivers to increase, the absence of aging implied by their findings provides strong evidence for the absence of recent large-scale warming there.

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4.2.4.3.3 The Past One to Two Centuries

The IPCC contends current temperatures are both unnatural and unprecedented, as a result of global warming caused by anthropogenic CO_2 emissions, and they claim this "unnaturalness" is most strongly expressed in the world's Arctic regions. Here we investigate that claim in the context of the past one to two centuries.

The studies reviewed here lead to the conclusion that, in spite of the model-based concerns about the Arctic being at a "tipping point" and beginning to experience unprecedented warming and irreversible ice loss, there is nothing unusual, unnatural, or unprecedented about current Arctic temperatures. Warming over the past three decades or so has been generally less impressive than a similar warming that occurred several decades earlier in the 1920s–1940s, and it becomes still less impressive when taking into consideration the atmosphere's CO_2 concentration rose by only about 5 ppm during the earlier period of stronger warming but by fully 25 ppm during the later period of weaker warming.

4.2.4.3.3.1 Greenland

Comiso *et al*. (2001) utilized satellite imagery to analyze and quantify several attributes of the Odden ice tongue, a winter ice-cover phenomenon that occurs in the Greenland Sea with a length of about 1,300 km and an aerial coverage of as much as 330,000 square kilometers, including its average concentration, maximum area, and maximum extent over the period 1979–1998. In addition, they used surface air temperature data from Jan Mayen Island, located within the region of study, to infer the behavior of the phenomenon over the past 75 years.

The Odden ice tongue was found to vary in size, shape, and length of occurrence during the 20-year period, displaying a fair amount of interannual variability. Trend analyses revealed the ice tongue had exhibited no statistically significant change in any of the parameters studied over the short 20-year period, but a proxy reconstruction for the past 75 years revealed the ice phenomenon to have been "a relatively smaller feature several decades ago," due to the significantly warmer temperatures that prevailed at that time.

The Odden ice tongue's persistence, virtually unchanged in the mean during the past 20 years, is in direct contrast with model predictions of rapid and increasing warmth in Earth's polar regions as a result of CO_2-induced global warming. This observation, along with the evidence from Jan Mayen Island that temperatures there actually cooled at a rate of 0.15 ± 0.03°C per decade during the past 75 years, confirms there has been little or no warming in this part of the Arctic over the past seven decades.

Hanna and Cappelen (2003) determined the air temperature history of coastal southern Greenland from 1958–2001 based on data from eight Danish Meteorological Institute stations in coastal and near-coastal southern Greenland, as well as the concomitant sea surface temperature (SST) history of the Labrador Sea off southwest Greenland based on three previously published and subsequently extended SST datasets (Parker *et al*., 1995; Rayner *et al*., 1996; Kalnay *et al*., 1996). The coastal temperature data showed a cooling of 1.29°C over the period of study, while two of the three SST databases also depicted cooling: by 0.44°C in one case and by 0.80°C in the other. The land-based air temperature and SST series followed similar patterns and were strongly correlated, but with no obvious lead/lag either way. In addition, the researchers determined the cooling was "significantly inversely correlated with an increased phase of the North Atlantic Oscillation (NAO) over the past few decades." The two researchers state this "NAO-temperature link doesn't explain what caused the observed cooling in coastal southern Greenland but it does lend it credibility." In referring to what they call "this important regional exception to recent 'global warming,'" Hanna and Cappelen note the "recent cooling may have significantly added to the mass balance of at least the southern half of the [Greenland] Ice Sheet." Since this part of the ice sheet would likely be the first to experience melting in a warming world, it would appear whatever caused the cooling has not only protected the Greenland Ice Sheet against warming-induced disintegration but actually fortified it against that possibility.

Taurisano *et al*. (2004) studied the temperature history of the Nuuk fjord during the past century, and their analyses of all pertinent regional data led them to conclude "at all stations in the Nuuk fjord, both the annual mean and the average temperature of the three summer months (June, July and August) exhibit a pattern in agreement with the trends observed at other stations in south and west Greenland (Humlum 1999; Hanna and Cappelen, 2003)." They report the temperature data "show that a warming trend occurred in the Nuuk fjord during the first 50 years of the 1900s, followed by a cooling over the second part of the century, when the average annual temperatures decreased by approximately 1.5°C." Coincident with this cooling trend there was "a remarkable increase in the number of snowfall days (+59 days)." Moreover, they report "not only did the cooling affect the winter months, as suggested by Hannna and Cappelen (2002), but also the summer mean," noting "the summer cooling is rather important information for glaciological studies, due to the ablation-temperature relations."

Chylek *et al*. (2004) analyzed data from three coastal stations in southern and central Greenland that possessed almost uninterrupted temperature records between 1950 and 2000, discovering "summer temperatures, which are most relevant to Greenland ice sheet melting rates, do not show any persistent increase during the last fifty years." Working with the two stations with the longest records (both over a century in length), they determined coastal Greenland's peak temperatures occurred between 1930 and 1940, and the subsequent decline in temperature was so substantial and sustained that temperatures at the end of the millennium were "about 1°C below their 1940 values." They also found "at the summit of the Greenland ice sheet the summer average temperature has decreased at the rate of 2.2°C per decade since the beginning of the measurements in 1987." Therefore, much of Greenland did not experience any net warming, but rather cooled significantly, over the most dramatic period of atmospheric CO_2 increase on record.

At the start of the twentieth century, however, Greenland was warming, as it emerged, along with the rest of the world, from the depths of the Little Ice Age. Between 1920 and 1930, when the atmosphere's CO_2 concentration rose by a mere 3 to 4 ppm, there was a phenomenal warming at all five coastal locations for which contemporary temperature records are available. Chylek *et al*. report, "average annual temperature rose between 2 and 4°C [and by as much as 6°C in the winter] in less than ten years." This warming, they note, "is also seen in the $^{18}O/^{16}O$ record of the Summit ice core (Steig *et al*., 1994; Stuiver *et al*., 1995; White *et al*., 1997)."

In commenting on this dramatic temperature rise, which they call the great Greenland warming of the 1920s, Chylek *et al*. conclude, "since there was no significant increase in the atmospheric greenhouse gas concentration during that time, the Greenland warming of the 1920s demonstrates a large and rapid temperature increase can occur over Greenland, and perhaps in other regions of the Arctic, due to internal climate variability such as the NAM/NAO [Northern Annular Mode/North Atlantic Oscillation], without a significant anthropogenic influence."

Laidre and Heide-Jorgensen (2005) published a somewhat unusual paper, in that it dealt with the danger of oceanic cooling. Using a combination of long-term satellite tracking data, climate data, and remotely sensed sea-ice concentrations to detect localized habitat trends of narwhals in Baffin Bay between Greenland and Canada, home to the largest narwhal population in the world, they studied the species' vulnerability to recent and possible future climate trends. They report, "since 1970, the climate in West Greenland has cooled, reflected in both oceanographic and biological conditions (Hanna and Cappelen, 2003)," with the result that "Baffin Bay and Davis Strait display strong significant increasing trends in ice concentrations and extent, as high as 7.5% per decade between 1979 and 1996, with comparable increases detected back to 1953 (Parkinson *et al*., 1999; Deser *et al*., 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002; Stern and Heide-Jorgensen, 2003)."

The two researchers also report, "cetacean occurrence is generally negatively correlated with dense or complete ice cover due to the need to breathe at the surface," and "lacking the ability to break holes in the ice," narwhals are vulnerable to reductions in the amount of open water available to them, as has been demonstrated by ice entrapment events "where hundreds of narwhals died during rapid sea ice formation caused by sudden cold periods (Siegastad and Heide-Jorgensen, 1994; Heide-Jorgensen *et al*., 2002)." Such events were becoming increasingly likely as temperatures continued to decline and sea-ice cover and variability increased, and the scientists found the latter two trends to be "highly significant at or above the 95% confidence level." They conclude, "with the evidence of changes in sea ice conditions that could impact foraging, prey availability, and of utmost importance, access to the surface to breathe, it is unclear how narwhal sub-populations will fare in light of changes in the high Arctic."

Chylek *et al*. (2006) studied the characteristics of two century-long temperature records from southern coastal Greenland—Godthab Nuuk on the west and Ammassalik on the east, both close to 64°N latitude—concentrating on the period 1915–2005. As they describe it, "although the whole decade of 1995–2005 was relatively warm, the temperatures at Godthab Nuuk and Ammassalik were not exceptionally high," as "almost all decades between 1915 and 1965 were warmer than, or at least as warm as, the 1995 to 2005 decade, suggesting the current warm Greenland climate is not unprecedented and that similar temperatures were [the] norm in the first half of the 20th century." They also note "two periods of intense warming (1995–2005 and 1920–1930) are clearly visible in the Godthab Nuuk and Ammassalik temperature records," but "the average rate of warming was considerably higher within the 1920–1930 decade than within the 1995–2005 decade." They report the earlier warming rate was 50 percent greater than the most recent one.

In comparing the southern coastal Greenland temperature record with that of the entire globe for the same time period, Chylek *et al*. note, "while all the decadal averages of the post-1955 global temperature are higher than the pre-1955 average, almost all post-1995 temperature averages at Greenland stations are lower than the pre-1955 temperature average." The three researchers also note, "the summer temperature at the Summit of the Greenland ice sheet shows a decreasing tendency since the beginning of the measurements in 1986 (Chylek *et al*., 2004)."

In light of these observations, Chylek *et al*. say, "An important question is to what extent can the current (1995–2005) temperature increase in Greenland coastal regions be interpreted as evidence of man-induced global warming?" They note "the Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary condition for [a] period of warming to arise," and "the observed 1995–2005 temperature increase seems to be within [the] natural variability of Greenland climate." In addition, "a general increase in solar activity (Scafetta and West, 2006) since [the] 1990s can be a contributing factor, as well as the sea surface temperature changes of [the] tropical ocean (Hoerling *et al*., 2001)."

Chylek *et al*. note, "glacier acceleration observed during the 1996–2005 period (Rignot and Kanagaratnam, 2006) has probably occurred previously," and "there should have been the same or more extensive acceleration during the 1920–1930 warming as well as during the Medieval Warm Period in Greenland (Dahl-Jensen *et al*., 1998; DeMenocal *et al*., 2000) when Greenland temperatures were generally higher than today." As Chylek *et al*. put it, "we find no direct evidence to support the claims that the Greenland ice sheet is melting due to increased temperature caused by increased atmospheric concentration of carbon dioxide."

Hansen *et al*. (2006) analyzed meteorological data from Arctic Station (69°15'N, 53°31'W) on-Disko Island (West Greenland) for the period 1991–2004, after which their results were correlated "to the longest record available from Greenland at Ilulissat/Jakobshavn (since 1873)." Marked changes were noted over the study period, including "increasing mean annual air temperatures on the order of 0.4°C per year and 50% decrease in sea ice cover." In addition, due to "a high correlation between mean monthly air temperatures at the two stations (1991–2004)," Hansen *et al*. placed the air temperature trend observed at Disko "in a 130 years perspective." This led them to conclude the climate changes of the last decade were "dramatic," but "similar changes in air temperatures [had] occurred previous[ly] within the last 130 years." They report the changes they observed over the last decade "are on the same order as changes [that] occurred between 1920 and 1930."

Drinkwater (2006) "provide[d] a review of the changes to the marine ecosystems of the northern North Atlantic during the 1920s and 1930s and … discuss[ed] them in the light of contemporary ideas of regime shifts," where he defined regime shift as "a persistent radical shift in typical levels of abundance or productivity of multiple important components of the marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent." He first determined "in the 1920s and 1930s, there was a dramatic warming of the air and ocean temperatures in the northern North Atlantic and the high Arctic, with the largest changes occurring north of 60°N," and this warming "led to reduced ice cover in the Arctic and subarctic regions and higher sea temperatures," as well as northward shifts of multiple marine ecosystems. This change in climate occurred, he writes, "during the 1920s, and especially after 1925," when "average air temperatures began to rise rapidly and continued to do so through the 1930s," at which point "mean annual air temperatures increased by approximately 0.5–1°C and the cumulative sums of anomalies varied from 1.5 to 6°C between 1920 and 1940 with the higher values occurring in West

Greenland and Iceland." Thereafter, "through the 1940s and 1950s air temperatures in the northernmost regions varied but generally remained relatively high," declining in the late 1960s in the northwest Atlantic and slightly earlier in the northeast Atlantic. This cooling only recently has begun to be reversed in certain parts of the region.

In the realm of biology, the early twentieth century warming of North Atlantic waters "contributed to higher primary and secondary production," in the words of Drinkwater, and "with the reduced extent of ice-covered waters, more open water allow[ed] for higher production than in the colder periods." Cod "spread approximately 1200 km northward along West Greenland" and "migration of 'warmer water' species also changed with earlier arrivals and later departures." In addition, Drinkwater notes, "new spawning sites were observed farther north for several species or stocks while for others the relative contribution from northern spawning sites increased." Also, "some southern species of fish that were unknown in northern areas prior to the warming event became occasional, and in some cases, frequent visitors." Drinkwater concludes, "the warming in the 1920s and 1930s is considered to constitute the most significant regime shift experienced in the North Atlantic in the 20th century."

Vinther *et al*. (2006) combined early observational records from 13 locations along the southern and western coasts of Greenland to extend the overall temperature history of the region—which stretches from approximately 60 to 73°N latitude—back to AD 1784, adding temperatures for 74 complete winters and 52 complete summers to what previously was available to the public. The authors report, "two distinct cold periods, following the 1809 'unidentified' volcanic eruption and the eruption of Tambora in 1815, [made] the 1810s the coldest decade on record." They found "the warmest year in the extended Greenland temperature record [was] 1941, while the 1930s and 1940s [were] the warmest decades." Their newly lengthened record revealed there has been no net warming of the region over the past 75 years.

Approximately half of the Vinther *et al.* study region was located above the Arctic Circle, where CO_2-induced global warming is suggested by climate models to be most evident and earliest expressed. One thus would have expected to see southwestern coastal Greenland's air temperature responding vigorously to the 75 ppm increase in the atmosphere's CO_2 concentration since 1930, even if the models were only half-correct. But no net change in air temperature has occurred there in response to the 25 percent increase in the air's CO_2 content experienced over that period.

Mernild *et al*. (2008) described "the climate and observed climatic variations and trends in the Mittivakkat Glacier catchment in Low Arctic East Greenland from 1993 to 2005 ... based on the period of detailed observations (1993–2005) and supported by synoptic meteorological data from the nearby town of Tasiilaq (Ammassalik) from 1898 to 2004." The authors report, "the Mittivakkat Glacier net mass balance has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% per year." During the past century of general mass loss, they found "periods of warming were observed from 1918 (the end of the Little Ice Age) to 1935 of 0.12°C per year and 1978 to 2004 of 0.07°C per year." They state, "the warmest average 10-year period within the last 106 years was the period from 1936–1946 (-1.8°C)," while the second warmest period was from 1995–2004 (-2.0°C). In addition, they note "also on West Greenland the period 1936–1946 was the warmest period within the last 106 years (Cappelen, 2004)."

"Using a set of 12 coastal and 40 inland ice surface air temperature records in combination with climate model output," Box *et al*. (2009) reconstructed "long-term (1840–2007) monthly, seasonal, and annual spatial patterns of temperature variability over a continuous grid covering Greenland and the inland ice sheet," after which they compared "the 1919–32 and 1994–2007 warming episodes" and made "a comparison of Greenland ice sheet surface air temperature temporal variability with that of the Northern Hemisphere average." The near-surface air temperature history Box *et al*. derived for Greenland is reproduced in Figure 4.2.4.3.3.1.1, along with the corresponding history of Northern Hemispheric near-surface air temperature.

The four researchers determined "the annual whole ice sheet 1919–32 warming trend is 33% greater in magnitude than the 1994–2007 warming," and "in contrast to the 1920s warming, the 1994–2007 warming has not surpassed the Northern Hemisphere anomaly." They note "an additional 1.0°–1.5°C of annual mean warming would be needed for Greenland to be in phase with the Northern Hemisphere pattern." The results of Box *et al*. demonstrate there is nothing unusual, unnatural, or unprecedented about the nature of Greenland's 1994–2007 warming episode, when the atmosphere's CO_2 concentration rose by about

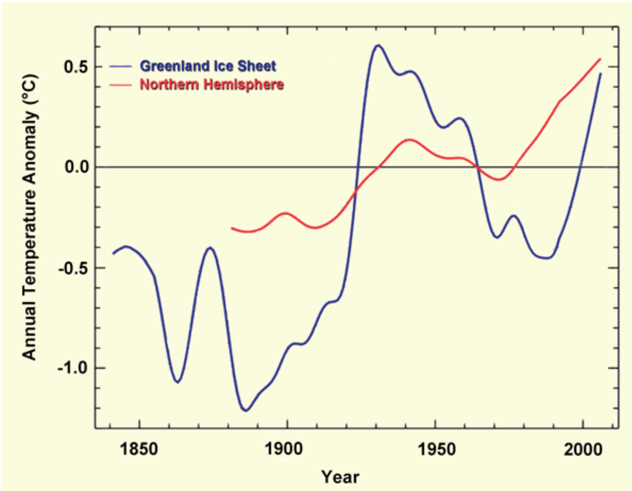

Figure 4.2.4.3.3.1.1. Low-pass-filtered Greenland and Northern Hemispheric near-surface air temperature anomalies with respect to the 1951-1980 base period vs. time. Adapted from Box, J.E., Yang, L., Bromwich, D.H., and Bai, L.-S. 2009. Greenland ice sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.

25 ppm, which is much less impressive than the 1919–1932 warming, when the atmosphere's CO_2 concentration rose by about 5 ppm.

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4.2.4.3.3.3 Russia/Asian Arctic

Zeeberg and Forman (2001) analyzed twentieth century changes in glacier terminus positions on north Novaya Zemlya, a Russian island located between the Barents and Kara Seas in the Arctic Ocean, providing a quantitative assessment of the effects of temperature and precipitation on glacial mass balance. This work revealed a significant and accelerated post-Little Ice Age glacial retreat in the first and second decades of the twentieth century, but by 1952, the region's glaciers had experienced 75–100% of their net twentieth century retreat. During the next 50 years the recession of more than half the glaciers stopped, and many tidewater glaciers began to advance.

These glacial stabilizations and advances were attributed by the two scientists to observed increases in precipitation and/or decreases in temperature. In the four decades since 1961, for example, weather stations at Novaya Zemlya show summer temperatures to have been 0.3 to 0.5°C colder than they were over the prior 40 years, while winter temperatures were 2.3 to 2.8°C colder. Zeeberg and Forman say such observations are "counter to warming of the Eurasian Arctic predicted for the twenty-first century by climate models, particularly for the winter season."

Polyakov *et al*. (2002) used newly available long-term Russian observations of surface air temperature from coastal stations to gain new insights into trends and variability in the Arctic environment poleward of 62°N. Throughout the 125-year history they developed, they identified "strong intrinsic variability, dominated by multi-decadal fluctuations with a timescale of 60–80 years" and found temperature trends in the Arctic to be highly dependent on the particular time period selected for analysis. They found they could "identify periods when Arctic trends were actually smaller or of different sign than Northern Hemisphere trends." Over the bulk of the twentieth century, however, when "multi-decadal variability had little net effect on computed trends," the temperature histories of the two regions were "similar" but did "not support amplified warming in polar regions predicted by GCMs."

Raspopov *et al*. (2004) presented and analyzed two temperature-related datasets: "a direct and systematic air temperature record for the Kola Peninsula, in the vicinity of Murmansk," which covered the period 1880–2000, and an "annual tree-ring series generalized for 10 regions (Lovelius, 1997) along the northern timberline, from the Kola Peninsula to Chukotka, for the period 1458–1975 in the longitude range from 30°E to 170°E," which included nearly all of northern Eurasia that borders the Arctic Ocean. The researchers' primary objectives were to identify any temporal cycles present in the two datasets and determine what caused them. They report discovering "climatic cycles with periods of around 90, 22–23 and 11–12 years," which were found to "correlate well with the corresponding solar activity cycles."

Of even more interest was what they learned about the temporal development of the Current Warm Period (CWP). Raspopov *et al.*'s presentation of the mean annual tree-ring series for the northern Eurasia timberline clearly shows the region's recovery from the coldest temperatures of the Little Ice Age (LIA) may be considered to have commenced as early as 1820 and was in full swing by at least 1840. It shows the rising temperature peaked just prior to 1950 and then declined to the end of the record in 1975. The Kola-Murmansk instrumental record indicates a significant temperature rise that peaked in the early 1990s at about the same level as the pre-1950 peak but then declined to the end of the record in 2000.

The last of these findings—that there was no net warming of this expansive high-latitude region over the last half of the twentieth century—is in harmony with the findings of the many studies we have reviewed here. The first first finding—that the thermal recovery of this climatically sensitive region of the planet began in the first half of the nineteenth century—is also supported by several other studies (Esper *et al*., 2002; Moore *et al*., 2002; Yoo and D'Odorico, 2002; Gonzalez-Rouco *et al*., 2003; Jomelli and Pech, 2004). All demonstrate the Little Ice Age-to-Current Warm Period transition began somewhere in the neighborhood of 1820 to 1850, well before the date (~1910) indicated in the Mann *et al.* (1998, 1999) "hockey stick" temperature history promulgated by the IPCC.

This difference is important, for it indicates the LIA-to-CWP transition in the Arctic was likely halfway or more complete before the Mann *et al.* temperature history suggests it even began, demonstrating most of the transition occurred well in advance of anthropogenic-caused increases in CO_2 emissions. That there was no net warming between somewhere in the 1930s or 1940s and the end of the twentieth century in the part of the world where CO_2-induced global warming is supposed to be most evident (the Arctic) makes it abundantly clear anthropogenic CO_2 emissions have had no discernible impact on any part of the LIA-to-CWP transition, the "global warming" some continue to claim is still occurring and can be stopped by reducing CO_2 emissions.

Groisman *et al*. (2006) write, "a new Global Synoptic Data Network consisting of 2100 stations within the boundaries of the former Soviet Union created jointly by the [U.S.] National Climatic Data Center and Russian Institute for Hydrometeorological Information was used to assess the climatology of snow cover, frozen and unfrozen ground reports, and their temporal variability for the period from 1936 to 2004." They determined "during the past 69 years (1936–2004 period), an increase in duration of the period with snow on the ground over Russia and the Russian polar region north of the Arctic circle has been documented by 5 days or 3% and 12 days or 5%, respectively," and they note this result "is in agreement with other findings."

Commenting on this development and the similar findings of others, the five researchers state, "changes in snow cover extent during the 1936–2004 period cannot be linked with 'warming' (particularly with the Arctic warming)" because "in this particular period the Arctic warming was absent."

Opel *et al*. (2009) worked with the uppermost 57 meters of a surface-to-bedrock ice core retrieved from the Akademii Nauk (AN) ice cap (~80°31'N, 94°49'E) of the Severnaya Zemlya archipelago (located in the central Russian Arctic between the Kara and Laptev Seas) to derive a $\delta^{18}O$ history covering the period 1883–1998. They compared this history with surface air temperatures (SATs) measured at 15 weather stations distributed throughout the Atlantic and Eurasian sub-Arctic, finding "good correlations and similarities." They note their $\delta^{18}O$ data also had "a strong correlation with the composite Arctic (north of 62° N) SAT anomalies time series of Polyakov *et al*. (2003)," demonstrating their $\delta^{18}O$ data can serve as a proxy for the region's SAT. They found "the $\delta^{18}O$ values show pronounced 20th-century temperature changes, with a strong rise about 1920 and the absolute temperature maximum in the 1930s." As shown in Figure 4.2.4.3.3.3.1, there was no net warming of the Atlantic and Eurasian sub-Arctic over the last 80 years of the twentieth century.

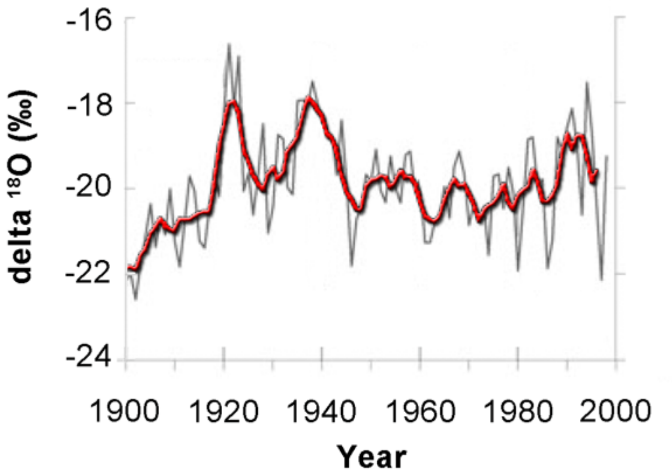

Figure 4.2.4.3.3.3.1. $\delta^{18}O$ (‰) vs. time (Years AD). Adapted from Opel, T., Fritzsche, D., Meyer, H., Schutt, R., Weiler, K., Ruth, U., Wilhelms, F., and Fischer, H. 2009. 115 year ice-core data from Akademii Nauk ice cap, Severnaya Zemlya: high-resolution record of Eurasian Arctic climate change. *Journal of Glaciology* **55**: 21–31.

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4.2.4.3.3.4 Scandinavia and Iceland

Humlum *et al*. (2005) note state-of-the-art climate models predict "the effect of any present and future global climatic change will be amplified in the polar regions as a result of feedbacks in which variations in the extent of glaciers, snow, sea ice and permafrost, as well as atmospheric greenhouse gases, play key roles." They also note Polyakov *et al*. (2002a,b) "presented updated observational trends and variations in Arctic climate and sea-ice cover during the twentieth century, which do not support the modeled polar amplification of surface air-temperature changes observed by surface stations at lower latitudes," and "there is reason, therefore, to evaluate climate dynamics and their respective impacts on high-latitude glaciers." They proceeded to do so for the Archipelago of Svalbard, focusing on Spitsbergen (the Archipelago's main island) and the Longyearbreen glacier located in its relatively dry central region at 78°13'N latitude.

Humlum *et al*. report, "a marked warming around 1920 changed the mean annual air temperature (MAAT) at sea level within only 5 years from about -9.5°C to -4.0°C," which "represents the most pronounced increase in MAAT documented anywhere in the world during the instrumental period." Then, they report, "from 1957 to 1968, MAAT dropped about 4°C, followed by a more gradual increase towards the end of the twentieth century."

Their work reveals the Longyearbreen glacier "increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years" and they state, "this example of late-Holocene glacier growth represents a widespread phenomenon in Svalbard and in adjoining Arctic regions," which they describe as a "development towards cooler conditions in the Arctic," which "may explain why the Little Ice Age glacier advance in Svalbard usually represents the Holocene maximum glacier extension."

Temperatures in Svalbard rose more rapidly in the early 1920s than has been documented anywhere else before or since, only to be followed by a nearly equivalent temperature drop four decades later, both of which were out of line with what climate models suggest should have occurred. The current location of the terminus of the Longyearbreen glacier suggests, even now, Svalbard and "adjoining Arctic regions" are still experiencing some of the lowest temperatures of the entire Holocene, at a time when atmospheric CO_2 concentrations are higher than they likely have been for millions of years. These observations are also at odds with what the IPCC claims about the strong warming power of rising atmospheric CO_2.There is little reason to put much confidence in the IPCC's claims, or to get too excited if the Arctic were to warm a bit—or even substantially and at a rapid rate. It has done so before, and it likely will do so again.

Hanna *et al*. (2006) developed a 119-year history of Icelandic Sea Surface Temperature (SST) based on measurements made at ten coastal stations located between latitudes 63°24'N and 66°32'N. This work revealed the existence of past "long-term variations and trends that are broadly similar to Icelandic air temperature records: that is, generally cold conditions during the late nineteenth and early twentieth centuries; strong warming in the 1920s, with peak SSTs typically being attained around 1940; and cooling thereafter until the 1970s, followed once again by warming—but not generally back up to the level of the 1930s/1940s warm period."

This brief section concludes with a short synopsis of a brief communication from Karlen (2005), in which he asks whether temperatures in the Arctic are "really rising at an alarming rate," as the models suggest they should be doing. His short answer is a resounding no; his explanation follows.

Focusing on Svalbard Lufthavn (located at 78°N latitude), which he later showed to be representative of much of the Arctic, Karlen reports "the Svalbard mean annual temperature increased rapidly from the 1910s to the late 1930s"; "the temperature thereafter became lower, and a minimum was reached around 1970"; and "Svalbard thereafter became warmer, but the mean temperature in the late 1990s was still slightly cooler than it was in the late 1930s," indicative of an actual cooling trend of 0.11°C per decade over the last 70 years of the twentieth century.

In support of his contention that cooling was the norm in the Arctic over this period, Karlen states "the observed warming during the 1930s is supported by data from several stations along the Arctic coasts and on islands in the Arctic, e.g. *Nordklim* data from Bjornoya and Jan Mayen in the north Atlantic, Vardo and Tromso in northern Norway, Sodankylaeand Karasjoki in northern Finland, and Stykkisholmur in Iceland." He also notes "there is also [similar] data from other reports; e.g. Godthaab, Jakobshavn, and Egedesmindde in Greenland, Ostrov Dikson on the north coast of Siberia, Salehard in inland Siberia, and Nome in western Alaska." All of these stations "indicate the same pattern of changes in annual mean temperature: a warm 1930s, a cooling until around 1970, and thereafter a warming, although the temperature remains slightly below the level of the late 1930s." In addition, "many stations with records starting later than the 1930s also indicate cooling, e.g. Vize in the Arctic Sea north of the Siberian coast and Frobisher Bay and Clyde on Baffin Island." Karlen reports the 250-year temperature record of Stockholm "shows that the fluctuations of the 1900s are not unique" and "changes of the same magnitude as in the 1900s occurred between 1770 and 1800, and distinct but smaller fluctuations occurred around 1825."

Noting the IPCC suggests the lion's share of the temperature increase during the 1920s and into the 1930s, which in the Arctic was the most dramatic warming of the twentieth century, was primarily due to solar effects (because the increase in CO_2 over this period was so small they had to go with something else), Karlen points out, "during the 50 years in which the atmospheric concentration of CO_2 has increased considerably, the temperature has decreased," which leads him to conclude "the Arctic temperature data do not support the models predicting that there will be a critical future warming of the climate because of an increased concentration of CO_2 in the atmosphere." As the first and only period of net warming in the Arctic occurred at a time when CO_2 could not have been its cause, it should be clear the modern theory of CO_2-induced global warming is an unreliable guide to the future.

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4.2.4.3.3.5 The Rest of the Arctic/Multiple Regions

Przybylak (2000) used mean monthly temperatures measured at 37 Arctic and 7 sub-Arctic stations, as well as temperature anomalies of 30 grid-boxes obtained from the updated dataset of Jones, to derive a number of spatial and temporal histories of Arctic near-surface air temperature. These analyses led the author to conclude, "In the Arctic, the highest temperatures since the beginning of instrumental observation occurred clearly in the 1930s." He reports, "even in the 1950s the temperature was higher than in the last 10 years"; "since the mid-1970s, the annual temperature shows no clear trend"; and "the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century." Przybylak concludes, "the observed variations in air temperature in the real Arctic are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect," because "the temperature predictions produced by numerical climate models significantly differ from those actually observed."

Two years later in a similar analysis, Przybylak (2002) examined intraseasonal (within season) and interannual (between years) variability in maximum, minimum, and average air temperature and diurnal air temperature range for the entire Arctic, as delineated by Treshnikov (1985), for the period 1951–1990, based on data from ten stations "representing the majority of the climatic regions in the Arctic." He found "trends in both the intraseasonal and interannual variability of the temperatures studied did not show any significant changes," leading Przybylak to conclude "this aspect of climate change, as well as trends in average seasonal and annual values of temperature investigated earlier (Przybylak, 1997, 2000), proves that, in the Arctic in the period 1951–90, no tangible manifestations of the greenhouse effect can be identified."

Polyakov *et al*. (2003) derived a surface air temperature history that stretched from 1875 to 2000, based on measurements carried out at 75 land stations and a number of drifting buoys located poleward of 62°N latitude. From 1875 to about 1917, the team of eight U.S. and Russian scientists found the surface air temperature of the northern region rose hardly at all, but then it climbed 1.7°C in just 20 years to reach a peak in 1937 that was not eclipsed over the remainder of the record. During this 20-year period of rapidly rising air temperature, the atmosphere's CO_2 concentration rose by a mere 8 ppm. Over the next six decades, when the air's CO_2 concentration rose by approximately 55 ppm—nearly seven times more than it had during the 20-year period of dramatic warming that preceded it—the surface air temperature of the region poleward of 62°N experienced no net warming and may have cooled.

Polyakov *et al*. (2004) developed a long-term history of Atlantic Core Water Temperature (ACWT) in the Arctic Ocean using high-latitude hydrographic measurements initiated in the late nineteenth century. They compared this history with the long-term history of Arctic Surface Air Temperature (SAT) developed a year earlier by Polyakov *et al*. (2003). The ACWT record revealed the existence of "two distinct warm periods from the late 1920s to 1950s and in the late 1980s–90s and two cold periods, one at the beginning of the record (until the 1920s) and another in the 1960s–70s." The SAT record depicted essentially the same thing, with the peak temperature of the latter warm period being not quite as high as the peak temperature of the former warm period. In the case of the ACWT record, this relationship was reversed, with the peak temperature of the latter warm period slightly exceeding the peak temperature of the former warm period. The most recent temperature peak was very short-lived and it rapidly declined, ending approximately 1°C cooler over the last few years of the record.

Like Arctic SATs, Arctic ACWTs are dominated "by multidecadal fluctuations with a time scale of 50–80 years," Polyakov *et al*. write. Both records indicate late twentieth century warmth was no different from that experienced in the late 1930s and early 1940s, offering no compelling reason to believe late twentieth century warmth was the result of CO_2-induced global warming, for the air's CO_2 concentration in the late 1930s and early 1940s was fully 80 ppm less than it is today.

Soon (2005) sought to determine whether rising atmospheric CO_2 concentration or variations in solar irradiance was the more dominant driver of twentieth century temperature change in the Arctic. He examined the roles the two variables may have played in forcing decadal, multi-decadal, and longer-term variations in surface air temperature (SAT), performing statistical analyses on a composite Arctic-wide SAT record constructed by Polyakov *et al*. (2003), global CO_2 concentrations taken from estimates made by the NASA GISS climate modeling group, and a total solar irradiance (TSI) record developed by Hoyt and Schatten (1993, updated by Hoyt in 2005) over the period 1875–2000.

Soon's analyses show a much stronger statistical relationship between SAT and TSI than between SAT and atmospheric CO_2 concentration. Solar forcing generally explained more than 75 percent of the variance in decadal-smoothed seasonal and annual Arctic temperatures, whereas CO_2 forcing explained only between 8 and 22 percent. Wavelet analysis further supported the case for solar forcing of SAT, revealing similar time-frequency characteristics for annual and seasonally averaged temperatures at decadal and multi-decadal time scales. In contrast, wavelet analysis gave little to no indication of a CO_2 forcing of Arctic SSTs. It would appear the Sun, not atmospheric CO_2, drove temperature change in the Arctic over the twentieth century.

Chylek *et al*. (2009) write, "one of the robust features of the AOGCMs [Atmosphere-Ocean General Circulation Models] is the finding that the temperature increase in the Arctic is larger than the global average, which is attributed in part to the ice/snow-albedo temperature feedback." They note "the surface air temperature change in the Arctic is predicted to be about two to three times the global mean," citing the IPCC (2007). Utilizing Arctic surface air temperature data from 37 meteorological stations north of 64°N, Chylek *et al*. explored the latitudinal variability in Arctic temperatures within two latitude belts—the low Arctic (64°N–70°N) and the high Arctic (70°N–90°N)—comparing the results with the mean measured air temperatures of these two regions over three periods: 1910–1940 (warming), 1940–1970 (cooling), and 1970–2008 (warming).

In initial apparent harmony with state-of-the-art AOGCM simulations, the five researchers report "the Arctic has indeed warmed during the 1970–2008 period by a factor of two to three faster than the global mean." The Arctic amplification factor was 2.0 for the low Arctic and 2.9 for the high Arctic. But that was the end of the real world's climate-change agreement with theory. During the 1910–1940 warming, for example, the low Arctic warmed 5.4 times faster than the global mean, while the high Arctic warmed 6.9 times faster. Even more out of line with climate model simulations were the real-world Arctic amplification factors for the 1940–1970 cooling: 9.0 for the low Arctic and 12.5 for the high Arctic.

These findings constitute yet another important example of the principle described and proven by Reifen and Toumi (2009): A model that performs well in one time period will not necessarily perform well in another time period. Since AOGCMs suffer from this shortcoming, they ought not be considered adequate justification for imposing dramatic cuts in anthropogenic CO_2 emissions, as their simulations of future temperature trends may be far different from what will actually transpire.

Ladd and Gajewski (2010) evaluated the position of the Arctic front—defined as "the semi-permanent, discontinuous front between the cold Arctic air mass and the intermediate Polar air mass, bounded in the south by the Polar Front (Oliver and Fairbridge, 1987)"—based on gridded data obtained from the National Center for Environmental Prediction/ National Center for Atmospheric Research reanalysis (NNR) for each July between 1948 and 2007, and from 1958 to 2002 using data from the European Centre for Medium-Range Weather Forecasts ERA-40, as well as the period 1948–1957 "for comparison with the results of Bryson (1966)." The two researchers report "the position of the July Arctic front varies significantly through the period 1948–2007," but they find it does so "with a mean position similar to that found by Bryson (1966)," which "close similarity is striking," they say, "given that the Bryson study was completed over 40 years ago."

Wood and Overland (2010) note "the recent widespread warming of the Earth's climate is the second of two marked climatic fluctuations to attract the attention of scientists and the public since the turn of the 20th century," and the first of these—"the major early 20th century climatic fluctuation (~1920–1940)"—has been "the subject of scientific enquiry from the time it was detected in the 1920s." They write "the early climatic fluctuation is particularly intriguing now because it shares some of the features of the present warming that has been felt so strongly in the Arctic." Wood and Overland reviewed what is known about the first warming through "a rediscovery of early research and new assessments of the instrumental record," which allowed them to compare what they learned about the earlier warming with what is known about the most recent one.

With respect to the first of the two warmings, the U.S. researchers say "there is evidence that the magnitude of the impacts on glaciers and tundra landscapes around the North Atlantic was larger during this period than at any other time in the historical period." In addition, "the ultimate cause of the early climatic fluctuation was not discovered by early authors and remains an open question," noting "all of the leading possibilities recognized today were raised by the 1950s, including internal atmospheric variability, anthropogenic greenhouse gas (CO_2) forcing, solar variability, volcanism, and regional dynamic feedbacks (e.g. Manley, 1961)." They add, "greenhouse gas forcing is not now considered to have played a major role (Hegerl *et al*., 2007)." Thus, they suggest "the early climatic fluctuation was a singular event resulting from intrinsic variability in the large-scale atmosphere/ocean/land system and that it was likely initiated by atmospheric forcing."

Wood and Overland conclude the "early climatic fluctuation is best interpreted as a large but random climate excursion imposed on top of the steadily rising global mean temperature associated with anthropogenic forcing." However, the early warming also could be interpreted as a large but random climate excursion imposed on top of the steadily rising global mean temperature associated with Earth's natural recovery from the global chill of the Little Ice Age. And there is no reason not to conclude the same about the most recent Arctic warming; in a major analysis of past rates of climate change in the Arctic, White *et al*. (2010) conclude, "thus far, human influence does not stand out relative to other, natural causes of climate change."

Wood *et al*. (2010) constructed a two-century (1802–2009) instrumental record of annual surface air temperature within the Atlantic-Arctic boundary region, using data obtained from "recently published (Klingbjer and Moberg, 2003; Vinther *et al*., 2006) and historical sources (Wahlen, 1886)" that yielded "four station-based composite time series" pertaining to Southwestern Greenland, Iceland, Tornedalen (Sweden), and Arkhangel'sk (Russia). This added 76 years to the previously available record. The credibility of their results, Wood *et al*. note, "is supported by ice core records, other temperature proxies, and historical evidence."

The U.S. and Icelandic researchers report the newly extended temperature history and their analysis of it reveal "an irregular pattern of decadal-scale temperature fluctuations over the past two centuries," of which the early twentieth century warming (ETCW) event—which they say "began about 1920 and persisted until mid-century"—was by far "the most striking historical example." Wood *et al*. write, "as for the future, with no other examples in the record quite like the ETCW, we cannot easily suggest how often—much less when—such a comparably large regional climate fluctuation might be expected to appear." Nevertheless, they state, "it would be reasonable to expect substantial regional climate fluctuations of either sign to appear from time to time" and, therefore, "singular episodes of regional climate fluctuation should be anticipated in the future." This conclusion also implies any rapid warming that may subsequently occur within the Atlantic-Arctic boundary region need not be due to rising greenhouse gas concentrations, as it could be caused by the same factor that caused the remarkable ETCW event.

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4.2.4.4 Asia

As indicated in the introduction of Section 4.2.4, numerous peer-reviewed studies reveal modern temperatures are not unusual, unnatural, or unprecedented. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration. This reality is further illustrated by the fact that conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 content remained at values approximately 30 percent lower than today's.

The following subsections highlight such research from Asia, where much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; the Current Warm Period is simply a manifestation of its latest phase. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to believe it is having any measurable impact on climate today.

4.2.4.4.1 China

Using a variety of climate records derived from peat, lake sediment, ice core, tree-ring, and other proxy sources, Yang *et al*. (2002) identified a period of exceptional warmth throughout China between AD 800 and 1100. Yafeng *et al*. (1999) also observed a warm period between AD 970 and 1510 in $\delta^{18}O$ data obtained from the Guliya ice cap of the Qinghai-Tibet Plateau, while Hong *et al*. (2000) developed a 6,000-year $\delta^{18}O$ record from plant cellulose deposited in a peat bog in the Jilin Province (42° 20’ N, 126° 22’ E), within which they found evidence of “an obvious warm period represented by the high $\delta^{18}O$ from around AD 1100 to 1200 which may correspond to the Medieval Warm Epoch of Europe” (see Figure 4.2.4.4.1.1).

Hong *et al*. (2000) had previously reported that at the time of the MWP, “the northern boundary of the cultivation of citrus tree (*Citrus reticulata* Blanco) and *Boehmeria nivea* (a perennial herb), both subtropical and thermophilous plants, moved gradually into the northern part of China, where it has been estimated that the annual mean temperature was 0.9–1.0°C higher than at present.” Considering the climatic conditions required to successfully grow these plants, they further note annual mean temperatures in that part of the country during the Medieval Warm Period must have been about 1.0°C higher than at present, with extreme January minimum temperatures fully 3.5°C warmer than they are today, citing De’er (1994).

Xu *et al*. (2002) also determined, from a study of plant cellulose $\delta^{18}O$ variations in cores retrieved from peat deposits at the northeastern edge of the Qinghai-Tibet Plateau, from AD 1100–1300 “the $\delta^{18}O$ of Hongyuan peat cellulose increased, consistent with that of Jinchuan peat cellulose and corresponding to the ‘Medieval Warm Period.’” Qian and Zhu (2002) analyzed the thickness of laminae in a stalagmite found in Shihua Cave, Beijing, from which they inferred the existence of a relatively wet period from approximately AD 940 to 1200.

Chu *et al*. (2002) studied the geochemistry of 1,400 years of dated sediments recovered from seven cores taken from three locations in Lake Huguangyan (21°9’N, 110°17’E) on the low-lying Leizhou Peninsula in the tropical region of South China, together with information about the presence of snow, sleet, frost, and frozen rivers over the past 1,000 years obtained from historical documents. They note “recent publications based on the phenological phenomena, distribution patterns of subtropical plants and cold events (Wang and Gong, 2000; Man, 1998; Wu and Dang, 1998; Zhang, 1994) argue for a warm period from the beginning of the tenth century AD to the late thirteenth century AD,” as their own data also suggest. In addition, they note there was a major dry period from AD 880–1260, and “local historical chronicles support these data, suggesting the climate of tropical South China was dry during the ‘Mediaeval Warm Period.’”

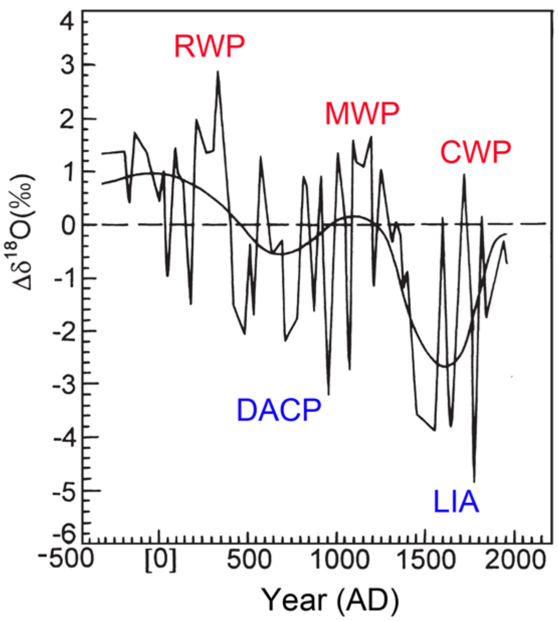

Figure 4.2.4.4.1.1. A 6,000-year $\delta^{18}O$ record from a peat bog in the Jilin Province. Adapted from Hong, Y.T., Jiang, H.B., Liu, T.S., Zhou, L.P., Beer, J., Li, H.D., Leng, X.T., Hong, B., and Qin, X.G. 2000. Response of climate to solar forcing recorded in a 6000-year $\delta^{18}O$ time-series of Chinese peat cellulose. *The Holocene* **10**: 1–7.

In an analysis of past sea-level history in the South China Sea, Zicheng *et al*. (2003) cite the work of Honghan and Baolin (1996, in Chinese), stating these authors found “the climate temperature at 1000 a B.P. is 1–2°C higher than that at present time,” referring to the Futian section on the eastern bank of the Pearl River, Shenzhen Bay, China (~22.5°N, 113.5°E). Zicheng *et al*. also cited the work of Baofu *et al*. (1997), who investigated palaeotemperatures of the coral reef at Dengloujao, Leizhou Peninsula, China (~20.25°N, 110°E) and report "sea-surface temperature at 1170 a B.P. is 2°C higher than that at present time."

Paulsen *et al*. (2003) used high-resolution $\delta^{13}C$ and $\delta^{18}O$ data derived from a stalagmite found in Buddha Cave (33°40'N, 109°05'E) to infer changes in climate in central China over the prior 1,270 years. Among the climatic episodes evident in their data were, they write, "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." The dry-then-wet-then-dry-again MWP began about AD 965 and continued to approximately AD 1475.

Ma *et al*. (2003) analyzed a stalagmite from Jingdong Cave, about 90 km northeast of Beijing, to assess the climatic history of the past 3,000 years at 100-year intervals on the basis of $\delta^{18}O$ data, the Mg/Sr ratio, and the solid-liquid distribution coefficient of Mg. The researchers found between 200 and 500 years ago "air temperature was about 1.2°C lower than that of the present," but between 1,000 and 1,300 years ago, there was an equally aberrant but warm period that "corresponded to the Medieval Warm Period in Europe."

Based on 200 sets of phenological and meteorological records extracted from a variety of historical sources, many of which are described by Gong and Chen (1980), Man (1990, 2004), Sheng (1990), and Wen and Wen (1996), Ge *et al*. (2003) produced a 2,000-year history of winter half-year temperature (October to April, when CO_2-induced global warming is projected to be most evident) for the region of China bounded by latitudes 27 and 40°N and longitudes 107 and 120°E. This work revealed a significant warm epoch from the AD 570s to the 1310s, the peak warmth of which was "about 0.3–0.6°C higher than present for 30-year periods, but over 0.9°C warmer on a 10-year basis" (see Figure 4.2.4.4.1.2).

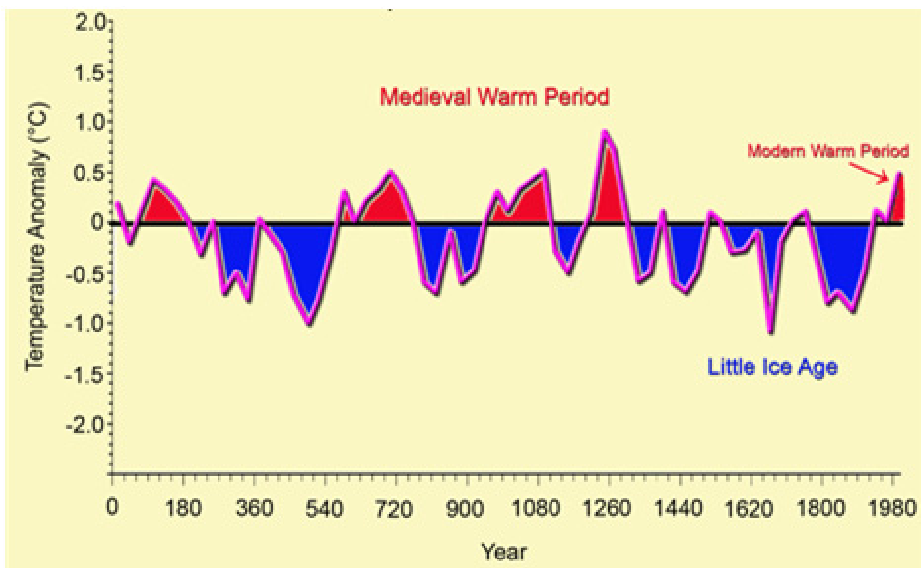

Figure 4.2.4.4.1.2. Winter half-year temperature anomalies for eastern China. Adapted from Ge, Q., Zheng, J., Fang, X., Man, Z., Zhang, X., Zhang, P., and Wang, W.-C. 2003. Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. *The Holocene* **13**: 933–940.

Zhu *et al*. (2003) worked with a sediment core extracted from lake Chen Co in the Yamzhog Yum Co drainage basin of southern Tibet in the delta of the Kaluxiong River, dated by comparing sedimentary rates measured by ^{210}Pb and absolute time horizons measured by ^{137}Cs (Wan 1997, 1999; Benoit and Rozan, 2001). Several environmentally related magnetic properties of sections of the core were measured and analyzed. This work revealed a "Middle Ages Warm-period" (around ca. 1120–1370 AD) followed by "an intensively cold stage during ca. 1550–1690 AD, a cold-humid stage from ca. 1690–1900 AD and a warm-dry stage since ca. 1900 AD." They note the warm period of the past century was not as warm as the earlier 250-year warm period of the Middle Ages.

Bao *et al*. (2003) utilized proxy climate records (ice-core $\delta^{18}O$, peat-cellulose $\delta^{18}O$, tree-ring widths, tree-ring stable carbon isotopes, total organic carbon, lake water temperatures, glacier fluctuations, ice-core CH_4, magnetic parameters, pollen assemblages, and sedimentary pigments) obtained from 20 prior studies to derive a 2,000-year temperature history of the northeastern, southern, and western sections of the Tibetan Plateau. In each case, there was more than one prior 50-year period when the mean temperature of each region was warmer than it was over the most recent 50-year period. In the case of the northeastern sector of the plateau, all of the maximum-warmth intervals occurred during the Medieval Warm Period; in the western sector, they occurred near the end of the Roman Warm Period; and in the southern sector they occurred during both warm periods. With respect to the entire Tibetan Plateau, the researchers found nothing extraordinary about the recent past. For the whole region, there was one prior 50-year period when temperatures were warmer than they were over the most recent 50-year period, and that was near the end of the Roman Warm Period, some 1850 years ago.

Bao *et al*. (2004) collected and analyzed proxy climate data derived from ice cores, tree rings, river and lake sediments, and lake terraces and paleosols, as well as historical documents, to determine the climatic state of northwest China during the Western and Eastern Han Dynasties (206 BC–AD 220) relative to the past two millennia. Their analysis revealed "strong evidence for a relatively warm and humid period in northwest China between 2.2 and 1.8 kyr BP," during the same time interval as the Roman Warm Period, which period experienced higher tempera-tures than those of today. They note "the warm-wet climate period during 2.2–1.8 kyr BP also occurred in central and east China, after [which] temperatures decreased rapidly (Zhu, 1973; Hameed and Gong, 1993; Yan *et al*., 1991, 1993; Shi and Zhang, 1996; Ge *et al*., 2002)." They found historical records report "an abrupt climate change from warmer and wetter to cooler and drier conditions occurred around AD 280 (Zhang *et al*., 1994)." In addition, "three alternate China-wide tempera-ture composites covering the last 2000 years display an obvious warm stage in 0–240 AD (Yang *et al*., 2002)," and "according to a 2650-year warm-season temperature reconstruction from a stalagmite from Shihua Cave of Beijing (Tan *et al*., 2003), the temperatures during 2.1–1.8 ka BP were basically above the average of the entire temperature series."

Bao *et al*. conclude, "the warm and moist conditions during the Western and Eastern Han Dynasties [i.e., the Roman Warm Period] might have been responsible for the large-scale agricultural production and the local socioeconomic boom that is documented by the occurrence of the famous ruin groups of Loulan, Niya, and Keriya." Citing the existence of plant remains such as walnuts, rice, barley, millet, and wheat grains found in the area, they also indicate the water and temperature conditions of the Roman Warm Period "were suitable for rice cultivation and much better than today."

Wei *et al*. (2004) measured high-resolution Sr/Ca ratios in two *Porites* corals off the coast of the Leizhou Peninsula in the northern South China Sea, using inductively coupled plasma atomic spectrometry, and their ages were determined via U-Th dating. The transfer function relating the Sr/Ca ratio to temperature was established on a modern *Porites lutea* coral by calibrating against sea surface temperatures (SSTs) measured from 1989 to 2000 at the nearby Haikou Meteorological Station. By these means one of the two coral sections was dated to AD 489–500 in the middle of the Dark Ages Cold Period, and the other was dated to 539–530 BC in the middle of the Roman Warm Period.

From the Dark Ages Cold Period portion of the coral record, Wei *et al*. determined the average annual SST was approximately 2.0°C colder than that of the last decade of the twentieth century (1989–2000), and from the Roman Warm Period portion of the record they obtained a mean annual temperature identical to that of the 1989–2000 period as measured at the Haikou Meteorological Station.

Yu *et al*. (2005) also derived high-resolution Sr/Ca ratios for *Porites lutea* coral samples taken off the coast of the Leizhou Peninsula and determined their ages by means of U-Th dating, and the transfer function relating the Sr/Ca ratio to temperature was obtained from a modern *P. lutea* coral in the same location by calibrating the ratio against SSTs measured from 1960 to 2000 at the Haikou Ocean Observatory. The researchers found the coral Sr/Ca ratio to be "an ideal and reliable thermometer," after which they employed it to reveal a coral sample dated to ~541 BC during the Roman Warm Period yielded "a mean of Sr/Ca-SST maxima of 29.3°C and a mean of Sr/Ca-SST minima of 19.5°C, similar to those of the 1990s (the warmest period of the last century)." Yu *et al*. say "historic records show that it was relatively warm and wet in China during 800–300 BC (Eastern Zhou Dynasty)," noting "it was so warm during the early Eastern Zhou Dynasty (770–256 BC) that rivers in today's Shangdong province (35–38°N) never froze for the whole winter season in 698, 590, and 545 BC."

Zhang *et al*. (2004) reconstructed the salinity history of Qinghai Lake (the largest inland saline lake in China) for the period AD 1100–2000 based on a relationship between the shell length of the ostracod *Limnocythere inopinata* and the salinity of the water in which it lives, a relationship developed by Yin *et al*. (2001) from data gathered from 50 lakes of different salinities scattered across the Tibetan Plateau. Zhang *et al*. used ostracod shell-length data derived from a 114-cm sediment core to discover "low salinity during 1160–1290 AD showed the humid climate condition [of] the Medieval Warm Period in this area, while the high salinity during 1410–1540 AD, 1610–1670 AD and 1770–1850 AD [prevailed during] the three cold pulses of the Little Ice Age with a dry climate condition," where the evidence for the occurrence of these warm and cold intervals came from the climate change studies of Yao *et al*. (1990) and Wang (2001).

Qinghai Lake's modern salinity has not reached even the halfway point between the near-record high salinity of the last cold extreme of the Little Ice Age and the record low salinity experienced during the Medieval Warm Period, suggesting the warmth recently experienced in this region of China is nowhere near that experienced during the Medieval Warm Period. The salinity drop marking the "beginning of the end" of the last stage of the Little Ice Age began sometime prior to 1850, in harmony with the Northern Hemisphere temperature history of Esper *et al*. (2002) but in striking contradiction of the Northern Hemisphere temperature history of Mann *et al*. (1998, 1999), which does not depict any increase in temperature until after 1910, some 60 years later.

Ji *et al*. (2005) applied reflectance spectroscopy to a sediment core taken from the southeastern basin of Qinghai Lake. Sediment redness, related to iron oxide content, was judged to be an indicator of paleoclimatic changes in the core. Lower redness values were found to correlate with light, laminated sediments "associated with cold periods including the Little Ice Age (LIA)," whereas "warm periods, e.g., Medieval Warm Period (MWP), ... were marked by the accumulation of reddish-colored sediments." Based upon these findings the MWP is observed to have been a long warm and wet period (AD 400–1200) sandwiched between the cold and dry spells of the Dark Ages Cold Period (100 BC–200 AD) and Little Ice Age (AD 1220–1600) (see Figure 4.2.4.4.1.3).

Liu *et al*. (2006a) developed a quantitative reconstruction of temperature changes over the past 3,500 years based on alkenone distribution patterns in a sediment core retrieved from Qinghai Lake, based on the alkenone unsaturation index ($U^{k}37$) and its simplified form ($U^{k'}37$), which they say "have been calibrated to growth temperatures of marine alkenone producers (Prahl *et al*., 1988)" and "to temperature changes in lacustrine settings on a regional scale (Chu *et al*., 2005; Zink *et al*., 2001)." They state their temperature record "based on $U^{k'}37$ clearly shows oscillating warm/cold periods," with periods at 0–200 yr BP, 500–1,100 yr BP, and 1,500–2,000 yr BP that were relatively warm and "could be related to the 20th-century warm period, the Medieval Warm Period, and the Roman Warm Period," and "cold periods at 200–500 yr BP and 1100–1500 yr BP [that] corresponded to the Little Ice Age and the Dark Ages Cold Period." In addition, their data indicate the peak warmth of the Roman Warm Period exceeded the temperature of the latter part of the twentieth century by about 0.4°C, and the peak warmth of the Medieval Warm Period exceeded the temperature of the latter part of the twentieth century by nearly 1°C. The existence of this millennial-scale oscillation of climate, with its prior periods of higher-than-current temperatures, clearly demonstrates there is nothing unusual about Earth's present climatic state.

Ge *et al*. (2004) introduce their study of two thousand years of reconstructed winter half-year temperatures of eastern China by stating, "it is important to study the temperature change during the past 2000 years for understanding the issues such as the greenhouse effect and global warming induced by human activities." They also note "China has advantages in reconstructing historical climate change for its abundant documented historical records and other natural evidence obtained from tree rings, lake sediments, ice cores, and stalagmites."

The five climate scientists found "an about 1350-year periodicity in the historical temperature change," which revealed a number of multi-century warm and cold periods. Preceding the Current Warm Period, for example, was the Little Ice Age (LIA), which "in China, began in the early 14th century (the 1320s) and ended in the beginning of the 20th century (the 1910s)." It included four cold stages and three short warming phases. The LIA, in turn, was preceded by the Medieval Warm Period, which Ge *et al*. say "began in the 930s and ended in the 1310s." It was composed of two warm stages, each of more than 100 years duration, and a shorter intervening cold stage.

Looking further back in time, the Chinese scientists found a cold period from the 780s to the 920s and a warm period from the 570s to the 770s, which was in turn preceded by a cold period from the 210s to the 560s, which they say "was the only one comparable with [the] LIA for the past 2000 years." This ultra-cold spell was the Dark Ages Cold Period that followed on the heels of the Roman Warm Period.

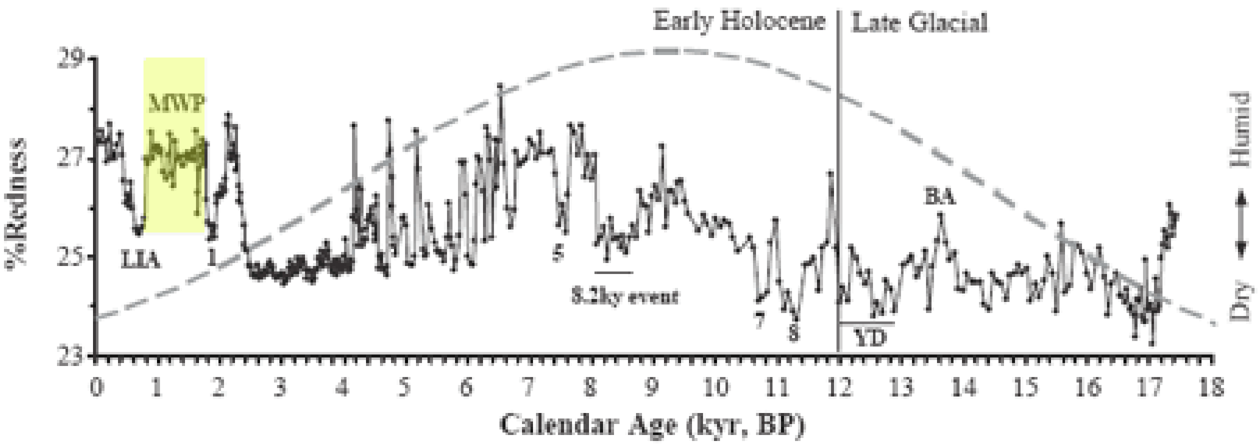

Figure 4.2.4.4.1.3. Qinghai Lake climate proxy showing the presence of the Little Ice Age and Medieval Warm Period as determined by the % redness value in a lake sediment core. Adapted from Ji, J., Shen, J., Balsam, W., Chen, J., Liu, L., and Liu, X. 2005. Asian monsoon oscillations in the northeastern Qinghai-Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters* **233**: 61–70.

Ge *et al*. state one of the purposes of their study was "to test whether the warming in the 20th century has exceeded the maximum magnitude in the past 2000 years." At the centennial scale, they report, "the temperature anomaly of the 20th century is not only lower than that of the later warm stage of the Medieval Warm Period (the 1200s~1310s), but also slightly lower than that of the warm period in the Sui and Tang dynasties (the 570s~770s) and the early warm stage of the Medieval Warm Period (the 930s~1100s)."

On a 30-year scale, they report, "the warmest 30-year temperature anomaly in the 20th century is roughly equal to the warmest 30-year one in the Sui and Tang dynasties warm period, but a little lower than that of the Medieval Warm Period." On the decadal scale, they note "the warmest decadal temperature anomaly in the 20th century is approximately at the same level of the warmest decade of the early stage of the Medieval Warm Period."

Ge *et al*. find "although the warming rate in the early 20th century has reached 1.1°C per century, such a rapid change is not unique during the alternation from the cold period[s] to the warm period[s]" of the prior 2,000 years. For example, they report the per-century warming rate from the 480s~500s to the 570s~590s was 1.3°C, from the 1140s~1160s to the 1230s~1250s was 1.4°C, and from the 1650s~1670s to the 1740s~1760s was 1.2°C.

Ge *et al*. say their analysis "gives a different viewpoint from that 'the 20th century is the warmest century in the past 1000 years', presented by IPCC, and is of great significance for better understanding the phenomena of the greenhouse effect and global warming etc. induced by human activities." With respect to what that "different viewpoint" might be, Ge *et al*. state it is that "the temperature of the 20th century in eastern China is still within the threshold of the variability of the last 2000 years."

Jin *et al*. (2004) analyzed percent organic carbon and Rb/Sr ratios in a sediment core extracted from the deepest part of Daihai Lake (112°32'–112°48'E, 40°28'–40°39'N) in Inner Mongolia, which they describe as being located "in the transitional zone between semi-arid and semi-humid conditions that is sensitive to East Asian monsoon variability." They found the data they obtained "support two distinct Little Ice Age cooling events centered at ~850 yr BP and ~150 yr BP," as well as "the Medieval Warm Period between 1200 and 900 yr BP," which they say "was warmer than the present, with higher chemical weathering than at present," citing Jin *et al*. (2002). Such findings echo the results of Zhangdong *et al*. (2002), who also used rubidium/strontium ratio, calcium carbonate, and organic concentration data of sediments cored from Daihai Lake (112°38'E, 40°33'N) to reconstruct the climate of that region over the past 2,200 years. Their results indicate the existence of a "warm and humid" climate that defined the Medieval Warm Period between AD 800 and 1100, which also exhibited the "strongest chemical weathering during the last 2,200 years."

Qiang *et al*. (2005) conducted stable carbon isotope analyses conducted on sediment cores taken from Lake Sugan (38°51.19'N, 93°54.09'E), located in the northeastern region of the Tibetan Plateau, to produce a proxy of winter temperatures over the past 2,000 years. The results indicate a warm and dry period between 580 and 1200 AD, which they state "corresponds to the Medieval Warm Period." The author's Figure 3 reveals the MWP was probably at least as warm between ~AD 1100 and 1200 as it is today.

Chen *et al*. (2009) studied varved sediments retrieved from cores extracted from Lake Sugan to develop a 1,000-year high-resolution (~10 years) salinity history of the lake, based on the relative abundances of chironomid species they identified via microscopic examination of head capsules found in the sediments. This work suggested, they write, "over the last millennium, the Sugan Lake catchment has alternated between contrasting climatic conditions, having a dry climate during the period AD 990–1550, a relative humid climate during the Little Ice Age (AD 1550–1840), and a dry climate again from AD 1840 onwards." They associate the first of the three periods with "the Medieval Warm Period in China," which they describe as being "warm and dry."

Li *et al*. (2006) conducted a variety of proxy analyses, including palynology, microfossil charcoal, stable isotopes ($\delta^{13}C$ and $\delta^{15}N$), and sediment geochemistry, on a 3.6-m sediment core taken from a relict oxbow lake in the Western Liaohe River Basin (42.07°N, 119.92°E) of northeastern China to reconstruct the environmental history of that region over the past 5,400 years. The results indicate the existence of a period of enhanced warmth and wetness from about AD 800 to 1400, which the researchers associate with the Medieval Warm Period.

Liu *et al*. (2006b) used three well-dated *Sabina Przewalskii* ring-width chronologies derived from 77 trees growing in three locations near Dulan, China on the northeastern Tibetan Plateau (36.0–36.3°N, 98.2–98.6°E) to reconstruct annual precipitation variations in that region over the period AD 850–2002. They compared their results with instrumental temperature data for that region at that time..

Working with 10-year moving averages, the 13 scientists found precipitation and temperature were "significantly correlated with r = 0.85 (p<0.0001), after the precipitation lagged temperature for 2 years." They produced a 40-year moving average curve that was "significantly correlated with seven temperature curves of the Northern Hemisphere," which led them to conclude their 40-year smoothed reconstruction "could be regarded as the millenary temperature curve for the northeastern Tibetan Plateau."

Liu, *et al*.'s "millenary temperature curve" clearly shows the 40-year-averaged temperature proxies in the vicinity of AD 915 are greater than those at the end of the twentieth century, which comprise the next highest peak of the record. Thus this study documents another specific instance where peak temperatures of the Medieval Warm Period likely were greater than peak temperatures of the twentieth century.

Jin *et al*. (2007) studied "the evolutionary history of permafrost in the central and eastern Qinghai-Tibetan Plateau since the end of the late Pleistocene, using relict permafrost and periglacial phenomena along the Qinghai-Tibet Highway from Gomud to Lhasa, the Qinghai-Kang (western Sichuan) Highway from Xi'ning to Yusu, adjacent areas, and the Xinjiang-Tibet Highway from Yecheng to Lhasa." They described permafrost and deduced environmental conditions during "the Megathermal period in the middle Holocene (~8500–7000 to ~4000–3000 years BP)" as well as "the warm period in the later Holocene (1000 to 500 years BP)." In comparing environmental and permafrost characteristics of those periods of elevated warmth with those of the present, the three researchers from the Chinese Academy of Sciences report "the total areas of permafrost [during the Megathermal period of the middle Holocene] were about 40–50% of those at present," while "mean annual air temperatures were ~2-3°C higher." Moreover, during the warm period of the late Holocene "the retreating of permafrost resulted in a total permafrost area of ~20–30% less than at present," and mean annual air temperatures were "1.5–2.0°C warmer than at present."

Liu *et al*. (2007) reconstructed a 1,000-year temperature history of the middle Qilian Mountains of China (37–39°N, ~99–103°E) at the convergence of the Qinghai-Xizang Plateau, the Inner Mongolia-Xinjiang Plateau, and the Loess Plateau, working with ring-width and $\delta^{13}C$ data derived from long-lived Qilian juniper (*Sabina przewalskii* Kom.) trees. Their reconstruction captured about 75 percent of the temperature variance over the calibration period 1960–2000 and correlated well with the Northern Hemisphere temperature reconstruction of Esper *et al*. (2002). As the six scientists describe it, the two sets of reconstructed temperature data (theirs and that of Esper *et al*) "reveal that the Medieval Warm Period and Little Ice Age were synchronous in China and the Northern Hemisphere." In addition, they note the two warmest intervals in their temperature reconstruction were 1060–1150 and 1900–2000, with corresponding peaks occurring around 1100 and 1999 that are essentially identical. Their results do not extend as far back in time as those of Esper *et al*., which rise to their highest level before Liu *et al*.'s history begins. Liu *et al*. acknowledge their reconstructed temperature history "has not included all of the Medieval Warm Period and, perhaps, not even its warmest period."

Ge *et al*. (2007) reviewed proxy temperature records of China that spanned the entire Holocene, focusing on the last two millennia, noting it is widely believed "increasing concentrations of greenhouse gases in the atmosphere are causing higher global atmospheric temperatures" and, therefore, "paleoclimate data are essential for both checking the predictions of climate models and characterizing the natural variability of [Earth's] climate system."

They found the warmest period of the Holocene occurred between 9,600 and 6,200 years ago, during portions of which temperatures "were about 1°C–5°C higher than the present in China." They also report "during the past two millennia, a warming trend in the 20th century was clearly detected, but the warming magnitude was smaller than the maximum level of the Medieval Warm Period," which they describe as having occurred between AD 900 and 1300. They state, "the Current Warm Period has lasted [only] 20 years from 1987 to 2006," and the annual mean temperature series of China since AD 1880 indicates the country was warmer in the mid-1940s than at the time of their study.

Tan *et al*. (2008) developed a precipitation history of the Longxi area of the Tibetan Plateau's northeast margin since AD 960 based on an analysis of Chinese historical records. They compared the result with the same-period Northern Hemisphere temperature record and contemporaneous atmospheric ^{14}C and ^{10}Be histories. This work revealed, "high precipitation of Longxi corresponds to high temperature of the Northern Hemisphere, and low precipitation of Longxi corresponds to low temperature of the Northern Hemisphere." They used their precipitation record to infer a Medieval Warm Period that stretched from about AD 960 to 1230, with temperature peaks in the vicinity of AD 1000 and 1215 that clearly exceeded the twentieth century peak temperature of the Current Warm Period. They also found "good coherences among the precipitation variations of Longxi and variations of atmospheric ^{14}C concentration, the averaged ^{10}Be record and the reconstructed solar modulation record." These findings harmonize, they write, with "numerous studies [that] show that solar activity is the main force that drives regional climate changes in the Holocene," in support of which they attached 22 scientific references. The four scientists conclude the "synchronous variations between Longxi precipitation and Northern Hemisphere temperature may be ascribed to solar activity," which apparently produced a Medieval Warm Period both longer and stronger than what has been experienced to date during the Current Warm Period in the northeast margin of the Tibetan Plateau.

Zhang *et al*. (2008) studied a stalagmite found in China's Wanxiang Cave (33°19'N, 105°00'E), which they say is located on the fringes of the area currently affected by the Asian Monsoon and is thus sensitive to (and integrates broad changes in) that annually recurring phenomenon. The 17 researchers developed a $\delta^{18}O$ record with an average resolution of 2.5 years that "largely anti-correlates with precipitation" and runs continuously from AD 190 to 2003. Zhang *et al*. demonstrate the record "exhibits a series of centennial to multi-centennial fluctuations broadly similar to those documented in Northern Hemisphere temperature reconstructions, including the Current Warm Period, Little Ice Age, Medieval Warm Period and Dark Age Cold Period." When one compares the peak warmth implied by their data for the Current and Medieval Warm Periods, it is easy to see the Medieval Warm Period was the warmer of the two.

Zhang *et al*. superimposed their $\delta^{18}O$ record upon individual plots of Northern Hemispheric temperature as derived by Esper *et al*. (2002), Moberg *et al*. (2003), and Mann and Jones (2003). In the first of these comparisons, the two records were closely matched, both indicating greater peak warmth during the Medieval Warm Period than during the Current Warm Period. The same was true of the second comparison, and in the third comparison the records also were closely matched over the majority of their expanse. Over the last decades of the twentieth century, however, the temperatures of the Mann and Jones record rise far above the temperatures implied by the Zhang *et al*. record (and, therefore, those of the Esper *et al*. and Moberg *et al*. records as well), suggesting this anomalous behavior of the Mann and Jones record is the result of a defect not found in the other three datasets. That defect is likely Mann and Jones' use of directly measured as opposed to reconstructed temperatures over their record's last few decades, which leads to their anomalous end-point "oranges" not telling the same story as told by everyone else's "apples."

It is also interesting to note the Zhang *et al.* record "correlates with solar variability, Northern Hemisphere and Chinese temperature, Alpine glacial retreat, and Chinese cultural changes." Since none of the last four phenomena can influence the first, it stands to reason solar variability is likely what has driven the variations in the other factors. In a commentary accompanying Zhang *et al.*'s article, Kerr (2008) notes the Zhang *et al.* record had been described by other researchers as "amazing," "fabulous," and "phenomenal," and it "provides the strongest evidence yet for a link among sun, climate, and culture." In addition, it provides equally strong evidence for at least the Northern-Hemispheric extent of the Medieval Warm Period and its greater and more persistent warmth than that of the Current Warm Period.

Based on a study of historical documents covering the period AD 1000–1950 and instrumental data from meteorological stations for the period 1950–2003, Zhang *et al.* (2008) developed a millennial-scale temperature index for the Yangtze Delta region of China that revealed "three distinct climate periods": the "Warm Medieval Period (AD 1000–1400), Little Ice Age (AD 1400–1920), and the ongoing well-established Global Warming Period (AD 1920–present)." This record documents a continuous period from about AD 1200 to 1235 when it was significantly warmer than the peak warmth recorded during the "well-established Global Warming Period." Similar results were found previously by Yi *et al.* (2006) , who analyzed arboreal pollen, non-arboreal pollen, and spores contained in a sediment core retrieved from the Changjiang prodelta (31°01.1'N, 122°47.0'E). This effort revealed, they write, "relatively warm/wet conditions comparable to [the] Medieval Warm Period (AD 910–1085) with a strengthen[ed] summer monsoon." Based on the findings of others, Yi *et al.* further state, "the mean temperature during this period was 1–2°C warmer than that of today."

Xiao *et al.* (2012) analyzed pollen, charcoal, and magnetic susceptibility data from a 150-cm-long sediment core extracted from the central portion of northern Taibai Lake (29°59'43"N, 115°48'27"E) in the middle reach of the Yangtze River. They concluded "vegetation changes [over the time interval AD 1050–1320] were mainly controlled by climatic changes, with limited influence from human activity," and this period was "more warm and humid" than those that preceded and followed it. They say these observations mean "the 'Medieval Warm Period' occurred in the middle reach of the Yangtze River," further noting "the reconstructed results of Ge *et al.* (2003, 2004) and the simulated results of Liu *et al.* (2005) also verified its existence in eastern China and even the whole of China."

Ma *et al.* (2008) analyzed multi-proxy data, including "^{14}C, grain size, microfossil, plant seeds, and geochemical elements," obtained from sediment retrieved from excavations made in the dry lake bed of Lop Nur China's West Lake (40°27'129" N, 90°20'083" E) in order "to amply discuss," as they describe it, "the climate and environment changes during the MWP," which they identify as occurring between AD 900 and 1300. They found the "sedimentary environment was stable around the MWP, with weak storm effect" and "the upper and lower sediments showed frequent strong storm effect." They also report "microfossils and plant seeds were abundant in this stage [MWP], which indicated a warm and humid fresh or brackish lake environment." Thereafter, "in the late period [AD 1300 to 1650], the environment turned worse, storm effect was intensified ... and the climate began to dry, leading to shriveling and death of many plants such as red willows." Ma *et al.* conclude "the environment was the best" over the period AD 1100 to 1300, stating, "temperature was almost the same [as] or a little higher than nowadays," providing another example of the widespread occurrence of the Medieval Warm Period, which they describe as "one of the most significant climate episodes in the world."

Yang *et al.* (2009) synthesized proxy records of temperature and precipitation in arid central Asia over the past two thousand years, focusing on the relationship between temperature and precipitation on timescales ranging from annual to centennial (Figure 4.2.4.4.1.4). With respect to temperature, they report "the most striking features are the existence of the Medieval Warm Period (MWP) and the Little Ice Age (LIA)," as well as the earlier Roman Warm Period (RWP) and Dark Ages Cold Period (DACP), plus what they call "a recent warming into the 20th century" they identify as the Current Warm Period (CWP). As for precipitation, the five researchers state the MWP "corresponded to an anomalously dry period whereas the cold LIA coincided with an

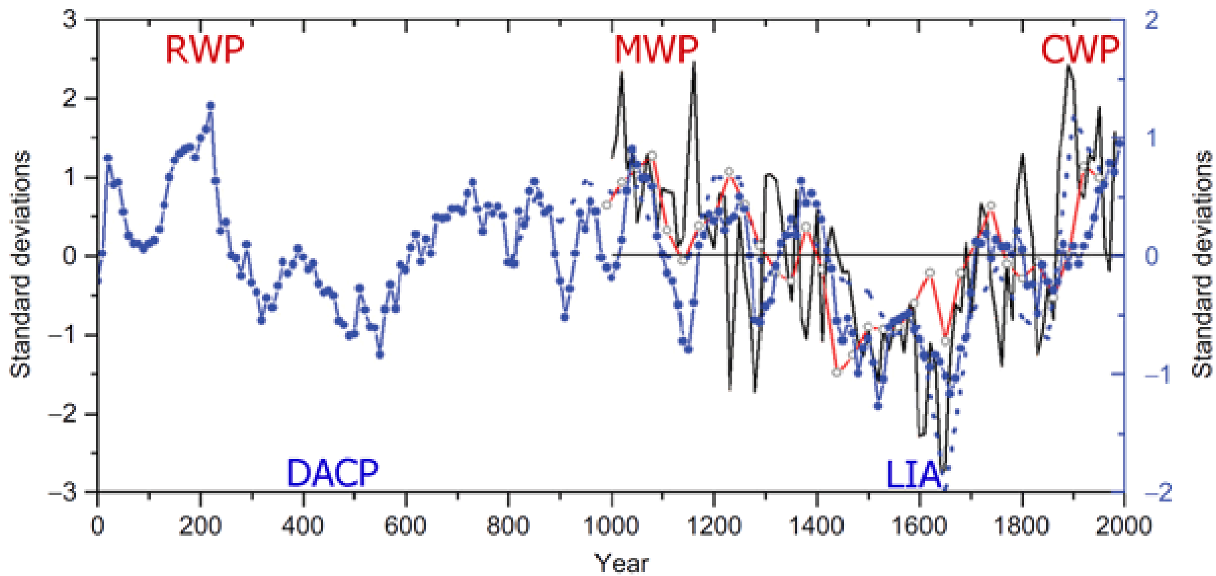

Figure 4.2.4.4.1.4. Standardized representations of various reconstructions of the temperature history of arid central Asia. Adapted from Yang, B., Wang, J., Brauning, A., Dong, Z., and Esper, J. 2009. Late Holocene climatic and environmental changes in arid central Asia. *Quaternary International* **194**: 68–78.

extremely wet condition." Once again, a substantive body of evidence is presented for the natural, non-CO_2-induced, millennial cycling of climate that has alternately brought the world into and then out of the Roman Warm Period, the Dark Ages Cold Period, the Medieval Warm Period, and the Little Ice Age, providing good reason to conclude the continuation of that cycle has likely brought the planet into the Current Warm Period and will ultimately bring the world out of its latest extended "heat wave."

Hong *et al*. (2009) write of the Medieval Warm Period, "because it is a distinct warm period nearest to the modern warming period and happened before the Industrial Revolution, it naturally becomes a [source of] comparison with modern warming." They add, "a universal concern in academic circles is [1] whether it also existed outside the European region and [2] whether it is a common phenomenon." In a study designed to broach both questions, they extracted cores of peat from a location close to Hani Village, Liuhe County, Jilin Province, China (42°13'N, 126°31'E) and used them to develop "a peat cellulose δ^{18}O temperature proxy record proximately existing for 14,000 years."

These efforts revealed the existince of the MWP on the Chinese mainland over the period AD 700–1400, peaking at about AD 900. The eight researchers report phenological data from east China (Ge *et al*., 2006) and tree-ring records from west China (Yang *et al*., 2000) also indicate "the temperature on the Chinese mainland was distinctly warmer during the MWP." They say MWP temperatures were as much as "0.9–1.0°C higher than modern temperatures (Zhang, 1994)."

Hong *et al*. further note, "sudden cooling events, such as the Older Dryas, Inter-Allerod, Younger Dryas, and nine ice-rafted debris events of the North Atlantic," described by Stuiver *et al*. (1995) and Bond *et al*. (1997, 2001), "are almost entirely reiterated in the temperature signals of Hani peat cellulose δ^{18}O." And "these cooling events show that the repeatedly occurring temperature cooling [and warming] pattern not only appeared in the North Atlantic Region in the high latitudes, but also in the Northwest Pacific Region in the middle latitudes," indicating the recurring warming and cooling occurred "outside the European region" and was "a common phenomenon."

Hong *et al*. also note the earlier paper of Hong *et al*. (2000), which describes a 6,000-year peat cellulose δ^{18}O record derived from nearby Jinchuan Town, Huinan County, Jilin Province, China (42°20'N, 126°22'E), identified δ^{18}O periodicities of 86, 93, 101, 110, 127, 132, 140, 155, 207, 245, 311, 590, 820 and 1,046 years, which they say "are similar to those detected in solar excursions" and which they consider "further evidence for a close relationship between solar activity and climate variations on timescales of decades to centuries."

The findings of Hong *et al*. (2000) were highly praised by Fairbridge (2001), who notes "almost identical equivalents are seen in solar emission periodicities and their harmonics, e.g., 86.884 years = 40 x 2.172 year Quasi Biennial Oscillation (QBO) as well as in the lunar tidal/apsides beat frequency (17.3769 years) which also matches closely with most of the longer spectral peaks, e.g., 140 (139) years, 207 (208.5), 311 (312.8), 590 (590.8) and 1046 (1042.6) years." For these spectacular spectral findings, Fairbridge writes, "Hong *et al*. deserve the appreciation of the entire Holocene community." And the case for a global and solar-induced Medieval Warm Period grows ever stronger, as it also does for the similar warm periods that preceded it in the prior 13,000 years, making the case for a similar origin for the Current Warm Period increasingly likely as well.

Liu *et al*. (2009) obtained a mean annual temperature history of the mid-eastern Tibetan Plateau based on Qilian juniper (*Sabina przewalskii*) tree-ring width chronologies obtained from living trees and archaeological wood for the 2,485-year period 484 BC–AD 2000, which data were calibrated against measured air temperatures for the period AD 1958–2000. They demonstrate their work to be well correlated with several temperature histories of the Northern Hemisphere. The eight researchers found four periods with average temperatures similar to "or even higher than" the mean of AD 1970–2000, beginning with the warm period of AD 401–413, which they say "was the warmest period within the last 2.5 thousand years." They also note an archaeological documentary record from Loulan in Xinjiang province shows pomegranate was employed as currency during the Eastern Jin Dynasty (AD 317–589), because the appearance of pomegranate during that period "suggests that the temperature at that time was higher than nowadays," citing Zhang and Zhang (2006). In addition, they note the rate of warming that led to the early ultra-warm period of their record was "unprecedented in the last 2500 years." And the last of the four ultra-warm periods was also slightly warmer than it was at the end of the twentieth century.

Liu *et al.* also suggest the high-temperature intervals of the AD 400–1000 period were relatively good times, as the downfalls of most of the major dynasties in China coincided with intervals of low temperature, citing the demise of the Qin, Three Kingdoms, Tang, Song (North and South), Yuan, Ming, and Qing Dynasties.

Chen *et al*. (2009) studied a sediment core taken from a mountain lake (Duck Pond, 25°10.441'N, 121°33.013'E) in Northern Taiwan that "represents deposition from AD 650 to present." They identified, measured, and analyzed "pollen, spores, diatoms, organic carbon, nitrogen, and $\delta^{13}C$ of organic matter in lake sediments to infer climate changes and reconstruct the paleo-environment of subtropical Taiwan over the past ~1300 years," temporally delineating five climate zones in the process. Zone III (AD 1050–1250) was "wet and warmer; ~MWP [Medieval Warm Period]", Zone IV (AD 1250–1790) was "wetter and colder than in Zone III; corresponding to LIA [Little Ice Age]," and Zone V (AD 1790–2000) was "drier and warmer than in Zone IV." They state, "in Europe and other regions, there was a short warm period (the medieval warm period, or MWP) prior to the LIA," and their "Zones III and IV likely correspond to such warm and cold periods." They also found the ratio of arboreal pollen (AP) to non-arboreal pollen (NAP) "showed a positive correlation with temperature" They report the peak AP/NAP ratio of the MWP was about three times greater than the peak AP/NAP ratio of the CWP, suggesting the peak warmth of the former period must have been considerably greater than the peak warmth of the latter period.

Wang *et al*. (2011) analyzed pollen data obtained from ten lake sediment cores and two land cores to assess the species abundances and alterations of forest-covered areas in northern Taiwan (23°17'N–25°18'N, 120°54'E–122°02'E) in response to changes in humidity and temperature over the past 2,000 years. The researchers found the climate of northern Taiwan was "wet and warm during 1000–500 cal. yr BP, which corresponded to the Medieval Warm Period (MWP)." They also note "an increased density and dispersal of *Tsuga* pollen corresponding to 500-200 cal. yr BP was observed, which corresponded to the Little Ice Age (LIA)." The authors' Figure 6, which presents a relationship between *Tsuga* pollen and temperature, shows the MWP was slightly warmer than the CWP.

Ge *et al*. (2010) write, "knowledge of past climate can improve our understanding of natural climate variability and also help address the question of whether modern climate change is unprecedented in a long-term context." They report "regional proxy temperature series with lengths of 500–2000 years from China have been reconstructed using tree rings with 1–3 year temporal resolution, annually resolved stalagmites, decadally resolved ice-core information, historical documents with temporal resolution of 10–30 years, and lake sediments resolving decadal to century time scales," noting "these proxies provide quantitative estimates of past climate through statistical calibration against instrumental temperature measurements."

Ge *et al*. divided China into five regions for their analysis and developed temperature reconstructions for each: three composite temperature reconstructions that extended back in time a full two millennia (Northeast, Tibet, Central East), one that extended back approximately 950 years (Northwest), and one that went back only about 550 years (Southeast). In the Northeast, the six scientists found a warm period "between approximately 1100 and 1200 that exceeded the warm level of the last decades of the 20th century." In Tibet, there was a "warming period of twenty decadal time steps between the 600s and 800s" that was "comparable to the late 20th century." In the Central East, there were two warm peaks (1080s–1100s and 1230s–1250s) with "comparable high temperatures to the last decades of the 20th century," although the graph of their data indicates these two periods were warmer than the last decades of the twentieth century. And in the Northwest, "comparable warm conditions in the late 20th century are also found around the decade 1100s."

Gen *et al*.'s work clearly shows there is nothing unusual, unnatural, or unprecedented about the country's current level of warmth. Thus there is no compelling reason to attribute late twentieth century warmth in China to twentieth century increases in the the atmospheric concentrations of CO_2 or any other greenhouse gases.

Shi *et al*. (2010) extracted 67 cores from 29 healthy trees in an old-growth forest in Nangcai, Zaduo County, at a site (32°39'36"N, 95°43'14"E) undisturbed by human activities. They developed a ring-width history covering the period AD 1360–2005 based on what they considered to be the best 46 cores from 23 trees. For the period AD 1961–2005, they derived a relationship between annual tree-ring width and directly measured May–June mean maximum air temperature, which they used to reconstruct a similar temperature history for the entire 645-year period. Based on an 11-year moving average of these results, they identified a 17-year warm period (AD 1438–1455), which occurred in the latter stages of the global MWP. As best as can be determined from the graphs of their results, this period was about 1.2°C warmer than the last decade of their temperature history (AD 1995–2005).

Li *et al*. (2010) developed a composite temperature history of the Hetao region of China stretching 5,000 years back in time from the early 2000s, based on pollen data from Daihai Lake (40°N, 112°E), oxygen isotope data from a salt lake in Yikezhaomeng, Inner Mongolia (39°N, 109°E), and total organic carbon data from Jingbian County (37°N, 108°E). This temperature history revealed "the climate was relatively warm" between 1450 and 1,000 calendar years before present (AD 550–1000), which "corresponded to the Medieval Warm Period." It is clear from their graph of the data that the peak warmth of the MWP was greater than the peak warmth of the CWP.

Zhou (2011), a scientist with the State Key Laboratory of Severe Weather of the Chinese Academy of Meteorological Sciences in Beijing, wrote in an introductory editorial in a special issue of the *Chinese Science Bulletin* (October 2011), "research on global climate change has been at the frontier of the contemporary sciences" and "debate has focused on whether the greenhouse effect produced by human activities is a major factor responsible for modern climate warming."

Zhou reports "in 2009, the major project 'Research on tree-ring and millennium climate change in China' was implemented under the support of the National Natural Science Foundation of China." Noting eight articles published in this special issue of the *Bulletin* "present partly preliminary results obtained by the project over the past two years," he summarizes their findings: The eight articles "reveal some characteristics and regularities of changes in temperature and precipitation in China and in East Asian monsoons over the past 1000 years" that qualify as "notable conclusions," of which he lists only two. But those two are extremely important: (1) "temperatures in the Medieval Warm Period are comparable to those in the current warm period over China," and (2) "the effect of solar activity on climate cannot be neglected in any period of the millennium."

Tian *et al*. (2011) reconstructed a 1,910-year-long time series—stretching from AD 2 to AD 1911—of outbreaks of Oriental migratory locusts in China, based on information the researchers extracted from more than 8,000 historical documents and relationships they developed between these data and indices of temperature at annual and decadal time scales. They found "a negative association between locust abundance and annual temperature," which was most strongly manifest when the temperature index was representative of the whole of China. As Figure 4.2.4.4.1.5 shows, the interval of lowest locust index during this period (~AD 1030–1250)—which would thus represent the warmest period of the record—falls right in the middle of the mean global Medieval Warm Period.

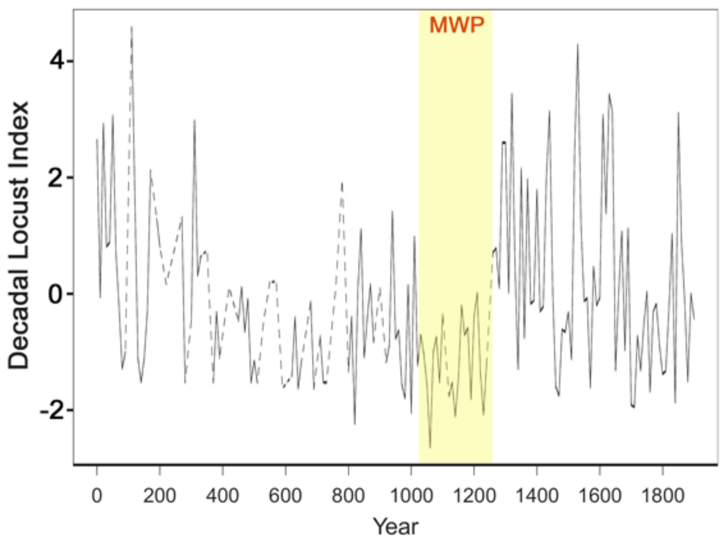

Figure 4.2.4.4.1.5. Chinese decadal locust abundance index vs. year. Dashed lines connect data points across periods with no locust reports. Adapted from Tian, H., Stige, L.C., Cazelles, B., Kausrud, K.L., Svarverud, R., Stenseth, N.C., and Zhang, Z. 2011. Reconstruction of a 1,910-y-long locust series reveals consistent associations with climate fluctuations in China. *Proceedings of the National Academy of Sciences USA* **108**: 14,521–14,526.

Wang *et al*. (2012) note "lakes are excellent sensors of environmental change" and "lake sediments can provide well-resolved records of change on different time scales." They also note "crater and maar lakes are especially sensitive to climate change because typically they have a small catchment area and limited inflow/outflow." Moreover, such lakes "often provide high-resolution records due to limnological processes favorable to the development and preservation of seasonally laminated sediments," citing Zolitschka *et al*. (2000). They add, "diatoms are excellent indicators of environmental conditions and have been widely used to reconstruct Holocene climate variability," citing Smol and Cumming (2000), Battarbee *et al*. (2001), and Mackay *et al*. (2003).

Wang *et al*. retrieved a 66.5-cm-long sediment core from Lake Erlongwan, one of eight maar lakes in the Long Gang Volcanic Field of Jilin Province, NE China (42°18'N, 126°21'E), which they describe as a closed dimictic lake that occupies an area of 0.3 km^2 and has a small catchment (0.4 km^2) with no natural inflows or outflow. They dated the sediment using radiometric ^{210}Pb, ^{137}Cs and ^{14}C analyses and analyzed it for diatom species and quantities. Although they note diatoms "are generally not known to be very sensitive to water temperature," they state, "climate affects the physical properties of the lake water column, especially as it controls the seasonal durations of ice cover, water column mixing and stratification, which all have profound effects on the availability of nutrients and light necessary for algal photosynthesis and growth." Thus "climate has an indirect influence on the composition and productivity of phytoplankton, especially non-motile organisms such as diatoms."

The ten researchers made "a detailed qualitative paleolimnological interpretation of the Lake Erlongwan sediment sequence based mainly on the growing body of literature that focuses on the ecology of planktonic diatoms, especially their responses to climate-driven changes in limnology." They report "three intervals were identified by their diatom assemblages and correspond within dating uncertainties to the Medieval Warm Period, the Little Ice Age and the 20th century warming trend." During the MWP, "the duration of the summer was longer while the spring and autumn were shorter than the 20th century." And they state "the period between ca. AD 1150 and 1200 was the warmest interval of the past 1000 years."

He *et al*. (2013) extracted sediment cores from the center of Lake Gahai (37°08'N, 97°31'E) and Lake Sugan (38°52'N, 93°75'E) and developed a decadally resolved alkenone-based temperature record for that part of the Qaidam Basin of the northern Tibetan Plateau that covered the last 2,600 and 2,200 years, respectively. Both records revealed the presence of the MWP between AD 700 and 1350. The ten Chinese researchers report regional temperatures during the peak warmth of the MWP, which occurred over the period AD 1100–1200 in Lake Gahai (see Figure 4.2.4.4.1.6) and AD 1000–1100 in Lake Sugan (see Figure 4.2.4.4.1.7), exceeded those in the recent warm period by approximately 1.9 and 4.0 °C, respectively.

The studies reviewed in this section make it clear that for a considerable amount of time during the Medieval Warm Period, most if not all of China exhibited warmer conditions than those of modern times. Those earlier high temperatures were caused by something other than elevated atmospheric CO_2 concentrations, and whatever was responsible for them also could be responsible for today's warmth. A growing body of evidence speaks to the reality of a global millennial-scale oscillation of climate totally independent of the air's CO_2 concentration. There is every reason to believe the most recent warming phase of this cycle, which ended the Little Ice Age and launched the Current Warm Period, was entirely natural and not the result of the coincidental increase in the air's CO_2 content.

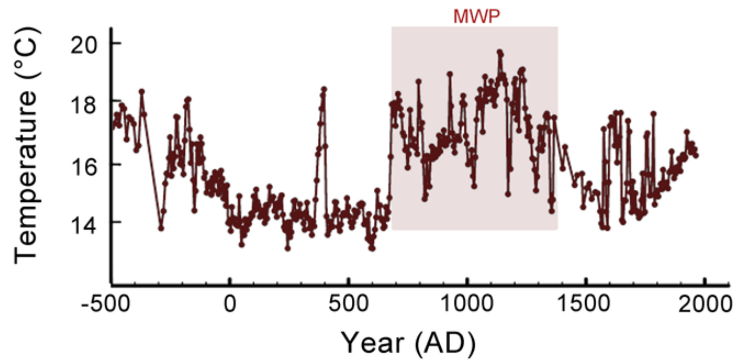

Figure 4.2.4.4.1.6. Alkenone-based temperature proxy from Lake Gahai. Adapted from He, Y.-X., Liu, W.-G., Zhao, C., Wang, Z., Wang, H.-Y., Liu, Y., Qin, X.-Y., Hu, Q.-H., An, Z.-S., and Liu, Z.-H. 2013. Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bulletin* **58**: 1053–1059.

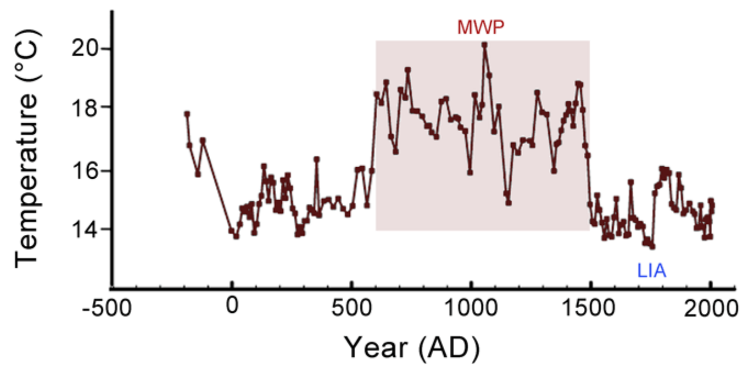

Figure 4.2.4.4.1.7. Alkenone-based temperature proxy from Lake Sugan. Adapted from He *et al*. (2013).

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4.2.4.4.2 Japan

The Medieval Warm Period (MWP) was a global climate anomaly that encompassed a few centuries on either side of AD 1000, when temperatures in many parts of the world were even warmer than they are currently. The degree of warmth and associated changes in precipitation varied from region to region, and the MWP was expressed somewhat differently in different parts of the world. How it manifested itself in Japan is the subject of this subsection.

Kitagawa and Matsumoto (1995) analyzed $\delta^{13}C$ variations of Japanese cedars growing on Yakushima Island, southern Japan (30°20'N, 130°30'E) to reconstruct a high-resolution proxy temperature record covering the past two thousand years. They applied spectral analysis to the $\delta^{13}C$ time series to determine if any significant periodicities were present in the data. They found significant decadal to centennial-scale variability throughout the record, with temperatures fluctuating by about 5°C across the series (see Figure 4.2.4.4.2.1). Most notable among the fluctuations were multi-century warm and cold epochs. Between AD 700 and 1200, for example, there was about a 1°C rise in average temperature, which "appears to be related to the 'Medieval Warm Period.'" In contrast, they found temperatures were about 2°C below the long-term pre-1850 average during the multi-century Little Ice Age that occurred between AD 1580 and 1700.

Kitagawa and Matsumoto also report finding significant temperature periodicities of 187, 89, 70, 55, and 44 years. Noting the 187-year cycle closely corresponds to the well-known Suess cycle of solar activity, and the 89-year cycle compares well with the Gleissberg solar cycle, they conclude their findings provide strong support for a Sun-climate relationship. Their findings also support the growing body of evidence indicating the Medieval Warm Period and Little Ice Age were global phenomena. They thus conclude there was nothing unusual, unnatural, or unprecedented about Current Warm Period temperatures in this region, which remain about one degree Celsius lower than the peak warmth of the Medieval Warm Period.

Noting instrumental climate records are insufficient to be used alone in understanding natural climate variability, Adhikari and Kumon (2001) analyzed the total organic carbon, total nitrogen, and sand content of sediment cores extracted from Lake Nakatsuna in central Japan (36°30'N, 137°51'E) to produce a proxy record of climate for this region that covered the past 1,300 years. This project revealed both the Medieval Warm Period (AD 900–1200), which the two researchers said was "warmer than any other period during the last 1300 years," and the Little Ice Age (AD 1200–1950), which was punctuated by three major cold phases (AD 1300–1470, 1700–1760 and 1850–1950). Their work thereby provides more evidence for a global Medieval Warm Period and a global Little Ice Age and suggests the Inter-governmental Panel on Climate Change (IPCC)

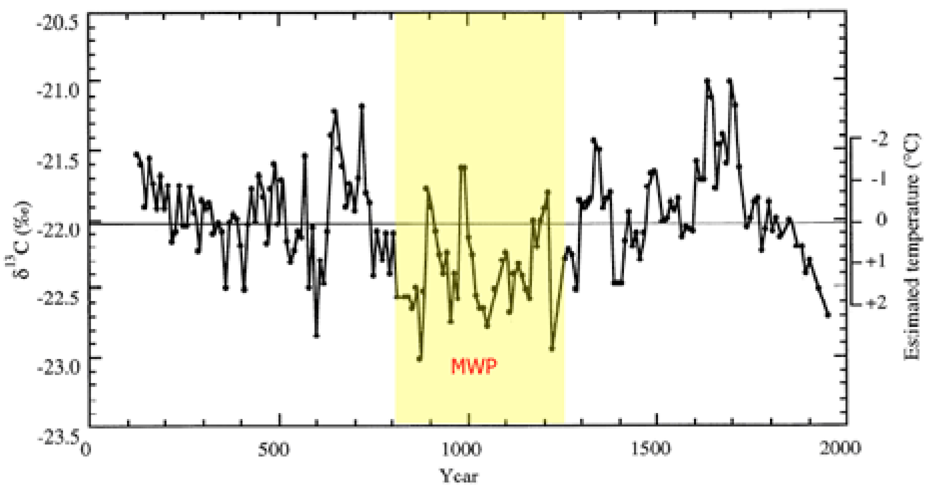

Figure 4.2.4.4.2.1. Proxy temperature record obtained from a $\delta^{13}C$ record of a giant Japanese cedar tree on Yakushima Island. Adapted from Kitagawa, H. and Matsumoto, E. 1995. Climatic implications of $\delta^{13}C$ variations in a Japanese cedar (*Cryptomeria japonica*) during the last two millennia. *Geophysical Research Letters* **22**: 2155–2158.

should never have abandoned its original climate history of the world—which more accurately depicted these significant temperature excursions (Houghton *et al*., 1990)—in favor of the flawed "hockey stick" temperature history of Mann *et al*. (1998, 1999).

Daimaru *et al*. (2002) write, "in snowpatch grasslands, plant distributions follow the contours of the snowmelt gradient around summer snowpatches," producing "similarly steep gradients in plant productivity and topsoil (e.g. Billings and Bliss, 1959; Helm, 1982; Kudo, 1991; Stanton *et al*., 1994.)" They state, "in the subalpine zone of northeastern Japan, sites where the snow cover disappears after July are usually occupied by 'snowpatch bare grounds' with extremely poor vegetation cover" that is "encircled by snowpatch grassland," citing Yamanaka (1979). As a result, "litter fall and the organic content in topsoil decrease toward the center of a snowpatch because the period for plant growth becomes shorter with delay in the time of snow disappearance," so in current "snowpatch grass-lands, peaty topsoil is restricted to sites where snowmelt comes early." The unique situation provided by a snowpatch can provide a good opportunity for paleoclimatic reconstructions based on vertical profiles of soil characteristics at various locations along transects moving outwards from summer snowpatches.

Daimaru *et al*. dug 27 soil pits at various locations in and around the center of a snowpatch grassland within a shallow depression of landslide origin on the southeastern slope of Japan's Mt. Zarumori (~39.8°N, 140.8°E), determining its age based on ^{14}C dating and tephrochronology. They state, "peaty topsoils were recognized at seven soil pits in the dense grassland, whereas sparse grassland lacked peaty topsoil." They also note, "most of the buried peat layers contained a white pumice layer named 'To-a' that fell in AD 915." This observation and the ^{14}C dating led them to conclude the buried peat layers in the poor vegetation area indicate "warming in the melt season" as well as "a possible weakened winter monsoon in the Medieval Warm Period," which their data suggest prevailed at the site throughout the tenth century; i.e., AD 900–1000. They observe "many studies have reported climatic signals that are correlated with the Medieval Warm Period from the 9th to 15th centuries in Japan," suggesting the possibly weakened winter monsoon of AD 900–1000 may have been a consequence of the warmer temperatures of that period.

Kitagawa *et al*. (2004) analyzed pollen in a sediment core retrieved from Karikomi Lake in the border area between the Hida and Echizen regions of Japan in the Hakusan mountains, as well as numerous local histories. They described the historical development of a practice called *hansaibai*, whereby local inhabitants encouraged the growth of horse-chestnut (*Aesculus turbinata*) trees as a food source during cold-induced famines of the Little Ice Age. Prior to that time, when the Medieval Warm Period prevailed, the mix of tree species in the local forest was that of "a warm temperate forest," they found. At about AD 1360, however, the warm-climate species "decreased, suggesting cooler climatic conditions," corresponding to "the beginning of the Little Ice Age as generally recognized in Japan (Sakaguchi, 1995)."

During this multi-century cold spell, Kitagawa *et al*. report "serious famines frequently occurred because of adverse climatic conditions," three of which were especially serious: "both the Kyoho famine in 1732 and the Tenmei famine (1782–1787) resulted in population decreases of about one million, and during the Tenpo famine (1823–1839) the population declined by ca. 290,000 (Nakajima, 1976)."

These observations clearly reveal the existence of both the Medieval Warm Period and Little Ice Age in Japan, strengthening the proposition that these distinctive climatic intervals were in fact global as opposed to merely regional phenomena restricted to countries bordering the North Atlantic Ocean. They also reveal the harshness of the Little Ice Age, which the five Japanese scientists say "caused serious famines in Europe, Argentina, and Mexico (Appleby, 1980; Cioccale, 1999; Post, 1984; Swan, 1981)," the latter two of which locations are also far removed from the North Atlantic Ocean.

Goto *et al*. (2005) reconstructed the ground surface temperature history from a borehole off the southern coast of Lake Biwa, the largest and oldest lake in Japan, to produce a proxy climate record spanning the past 3,000 years. The Medieval Warm Period was described as a period of warmth from the eighth to the twelfth century A.D. A comparison between the Medieval and Current Warm Periods could not be made because of anthropogenic and environmental factors influencing the record.

Isono *et al*. (2009) studied three sediment cores retrieved off the coast of central Japan in the northwestern Pacific Ocean (36°02'N, 141°47'E) to generate a multi-decadal-resolution record of alkenone-derived sea surface temperature (SST) that covers the full expanse of the Holocene. This record, they write, "showed centennial and millennial variability with an amplitude of ~1°C throughout the entire Holocene," and "spectral analysis for SST variation revealed a statistically significant peak with 1470-year periodicity." Isono *et al*. report, "SST minima centered at ca. 0.3 ka and ca. 1.5 ka are correlated with the Little Ice Age and the Dark Ages Cold Period in Europe, respectively, whereas the SST maximum centered at ca. 1.0 ka is correlated with the Medieval Warm Period." From data presented in the authors' Figure 2, it can be estimated the MWP was about 1°C warmer than the Current Warm Period.

Yamada *et al*. (2010) analyzed sediment cores they obtained in July 2007 from Lakes Ni-no-Megata (39°57'N, 139°43'E) and San-no-Megata (39°56'N, 139°42'E) on the Oga Peninsula of northeastern Japan, measuring a variety of properties including sulfur content and coarse mineral grains. The former served as a proxy for paleo-Asian summer monsoon activity, and the latter provided a proxy for paleo-Asian winter monsoon activity over the last two millennia. These data reveal the presence of a cold/dry interval from AD 1 to 750, a warm/humid interval from AD 750 to 1200, and another cold/dry interval from AD 1200 to the present. The scientists say these intervals could represent, respectively, "the Dark Ages Cold Period (DACP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA)."

They note their findings complement those of Kitagawa and Matsumoto (1995), whose study of tree-ring records in southern Japan "suggested the existence of one warm interval at AD 750–1300 and two cold intervals at AD 200–750 and AD 1600–1800," and the findings of Sakaguchi (1983), whose study of the pollen record of peaty sediments in central Japan revealed "an unusual warm interval (AD 700–1300) and a cool interval (ca. AD 250–700)." In addition, they write, the "strong summer monsoon and weak winter monsoon at Lakes Ni-no-Megata and San-no-Megata from AD 750–1200 correlates with the lower $\delta^{18}O$ values from Wangxiang Cave (Zhang *et al*., 2008) and lower values of minerogenic clastic content (Chu *et al*., 2009)." This is further evidence of the global scope of the millennial-scale oscillation of climate that reverberates throughout both glacial and interglacial periods.

Aono and Saito (2010) "investigated documents and diaries from the ninth to the fourteenth centuries to supplement the phenological data series of the flowering of Japanese cherry (*Prunus jamasakura*) in Kyoto, Japan, to improve and fill gaps in temperature estimates based on previously reported phenological data." They "reconstructed a nearly continuous series of March mean temperatures based on 224 years of cherry flowering data, including 51 years of previously unused data, to clarify springtime climate changes" and estimated other cherry full-flowering dates "from phenological records of other deciduous species, adding further data for six years in the tenth and eleventh centuries by using the flowering phenology of Japanese wisteria (*Wisteria floribunda*)."

The two researchers report their reconstruction "showed two warm temperature peaks of 7.6°C and 7.1°C, in the middle of the tenth century and at the beginning of the fourteenth century, respectively," and "the reconstructed tenth century temperatures [AD 900–1000] are somewhat higher than present temperatures after subtracting urban warming effects." They add, "the general pattern of change in the reconstructed temperature series in this study is similar to results reported by previous studies, suggesting a warm period in Asia corresponding to the Medieval Warm Period in Europe."

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4.2.4.4.2 Russia

Early evidence for the Medieval Warm Period in Russia was provided by Naurzbaev and Vaganov

(2000), who developed a 2,200-year proxy temperature record (212 BC to 1996 AD) using tree-ring data obtained from 118 trees near the upper timberline in Siberia. They conclude the warming experienced in the twentieth century was "not extraordinary," and "the warming at the border of the first and second millennia was longer in time and similar in amplitude."

Demezhko and Shchapov (2001) studied a borehole extending to more than 5 km depth, reconstructing an 80,000-year history of ground surface temperature in the Middle Urals within the western rim of the Tagil subsidence (58°24' N, 59°44'E). This history revealed a number of climatic excursions, including, they write, the "Medieval Warm Period with a culmination about 1000 years ago." Several years later, and working along the eastern slope of the Ural Mountains (~50–58°N, ~57–62°E), Golovanova *et al*. (2012) employed temperature data obtained from 44 boreholes and calculated "the ground surface temperature at the maximum of the Medieval Warm Period in [AD] 1100–1200 was approximately the same as the present temperature."

Hiller *et al*. (2001) analyzed subfossil wood samples from the Khibiny mountains on the Kola Peninsula of Russia (67–68°N, 33–34°E) to reconstruct that region's climate history over the past 1,500 years. They determined between AD 1000 and 1300 the tree-line was located at least 100–140 m above its current elevation, which suggests, they write, mean summer temperatures during this "Medieval climatic optimum" were "at least 0.8°C higher than today" and "the Medieval optimum was the most pronounced warm climate phase on the Kola Peninsula during the last 1500 years."

Hantemirov and Shiyatov (2002) examined remains of subfossil Siberian larch trees in Holocene deposits of the Yamal Peninsula over an area stretching from approximately 67°15'N to 67°40'N and from 69°50'E to 71°E, which they used to develop a 4,000-year tree-ring width chronology covering the period 2000 BC to AD 1996. Based on a transfer function that yielded mean June–July air temperatures, which they developed from temperatures measured at a meteorological station 150 km southwest of their research area over the period AD 1883–1996, the two researchers transformed their tree-ring width chronology into a June–July summer air temperature history. Hantemirov and Shiyatov write, "relatively favorable conditions existed in 1200–900 BC, 100 BC–AD 200, and during the 'Medieval Optimum' (AD 700–1400)," the last of which they indicate was most pronounced over the time interval AD 1100–1350. From their Figure 11, which presents the reconstruction after applying a 20-year low-pass filter, it can be determined temperatures peaked during this interval about 0.5°C above those experienced at the end of the twentieth century.

Krenke and Chernavskaya (2002) reviewed what was known about the MWP within Russia and throughout the world based on historical, glaciological, and hydrologic evidence and dendrological, archaeological, and palynological data. They report, for example, "the northern margin of boreal forests in Canada was shifted [north] by 55 km during the MWP, and the tree line in the Rocky Mountains in the southern United States and in the Krkonose Mountains was higher by 100–200 m than that observed at the present time."

The two members of the Russian Academy of Sciences write, "the temperature averaged over the 20th century was found to be the highest among all centennial means, although it remained within the errors of reconstructions for the early millennium." But in reference to the "hockey stick" temperature reconstruction of Mann *et al*. (1998, 1999), they note, "one should keep in mind that the reconstructions of the early period were based nearly entirely on tree-ring data, which, because of the features of their interpretation, tend to underestimate low-frequency variations, so the temperatures of the Medieval Warm Period were possibly underestimated." They provide further evidence for that conclusion, reporting, "the limits of cultivated land or receding glaciers have not yet exceeded the level characteristic of the early millennium."

With respect to Russia, Krenke and Chernavskaya report large differences in several variables between the Little Ice Age (LIA) and MWP. They report, for example, an MWP to LIA drop of 1.5°C in the annual mean temperature of northern Eurasia. They also state, "the frequency of severe winters reported was increased from once in 33 years in the early period of time, which corresponds to the MWP, to once in 20 years in the LIA," additionally noting "the abnormally severe winters [of the LIA] were associated with the spread of Arctic air masses over the entire Russian Plain." They point out the data they used to draw these conclusions were "not used in the reconstructions performed by Mann *et al*.," which perhaps explains why the Mann *et al*. temperature history of the past millennium does not depict the coolness of the LIA or the warmth of the MWP nearly as well as the more appropriately derived temperature history of Esper *et al*. (2002).

Krenke and Chernavskaya point out "an analysis of climate variations over 1000 years should help reveal natural multi-centennial variations possible at present but not detectable in available 100–200-year series of instrumental records." Their research contradicts the claim twentieth century warming is outside the realm of natural variability and must therefore be due to anthropogenic CO_2 emissions. And in contradiction of another of Mann *et al*.'s contentions, Krenke and Chernavskaya unequivocally state "the Medieval Warm Period and the Little Ice Age existed globally."

Esper and Schweingruber (2004) analyzed treeline dynamics over western Siberia during the twentieth century by comparing nine undisturbed polar sites located between 59° and 106°E and 61° and 72°N. They merged the information in such a way that, they write, "larger-scale patterns of treeline changes are demonstrated, and related to decadal-scale temperature variations," while also relating current treeline positions to former treeline locations "by documenting in-situ remnants of relict stumps and logs."

The results showed two main pulses of northward treeline advance in the mid- and late-twentieth century. The first of these recruitment phases occurred between 1940 and 1960, and the second started around 1972 and lasted into the 1980s. These treeline advances corresponded closely to annual decadal-scale temperature increases. The two researchers note "the lack of germination events prior to the mid-20th century indicates this is an exceptional advance," but the relict stumps and logs found at most sites "show that this advance is part of a long-term reforestation process of tundra environments." They note, for example, "stumps and logs of *Larix sibirica* can be preserved for hundreds of years (Shiyatov, 1992)," and "above the treeline in the Polar Urals such relict material from large, upright trees were sampled and dated, confirming the existence, around AD 1000, of a forest treeline 30 m above the late 20th century limit (Shiyatov, 2003)." They also state, "this previous forest limit receded around 1350, perhaps caused by a general cooling trend (Briffa, 2000; Esper *et al*., 2002."

"Synchronous with the advance shown from the western Siberian network," Esper and Schweingruber write, a mid-twentieth century tree recruitment period was occurring in "central Sweden (Kullmann, 1981), northern Finland (Kallio, 1975), northern Quebec (Morin and Payette, 1984) and the Polar Urals (Shiyatov, 1992)." Considering this with their own results from Asia, they conclude, "these findings from Europe and North America support a circumpolar trend, likely related to a global climate warming pattern," thereby recognizing these data demonstrate the positive response of the biosphere to the warming that accompanied the demise of the Little Ice Age and the establishment of the Current Warm Period.

The international team of Kremenetski *et al.* (2004), composed of Russian, German, and U.S. scientists, conducted a multi-proxy study of climate-related factors in the Khibiny Mountains in the central part of the Kola Peninsula (67–68°N, 33–34°E), analyzing and dating a series of subfossil soil profiles buried in avalanche cones and living and subfossil pine trees. The researchers report finding "a period of exceptionally warm and dry conditions commenced at ca. AD 600 and was most pronounced between ca. AD 1000 and 1200." They note, "warmer summer temperatures during this period (coeval with the 'Medieval Warm Period' observed in other parts of Europe) are evident in a 100–140 m upward shift in the pine (*Pinus sylvestris* L.) limit." Applying a simple environmental lapse rate of 0.7°C/100 m to this finding, they state, "this warming can be estimated as being on the order of at least 1°C compared to the modern summer temperature." In addition, they report, "on average, the cellulose of pine trees that grew between ca. AD 1000 and 1300 is enriched by $\delta^{13}C$ values of around 1 [per mil] compared to the modern trees from the region, further suggesting warmer summer climate than at present." They also report "there was also a stabilization of slopes on avalanche cones and formation of soils on them" during this warmer and drier period. Finally, they note "this period of warming extends to northwestern Russia as well as other parts of Europe."

Solomina and Alverson (2004) reviewed and synthesized the findings of papers presented at a conference held in Moscow in May 2002, which brought together more than 100 local paleo-environmental researchers from Bellarussia, Estonia, Georgia, Kyrgyzstan, Russia, Ukraine, and Uzbekistan, plus another 30 scientists from 18 other countries. The two researchers summarized the meeting's overall findings for five distinct regions: the Arctic and Sub-Arctic, the Russian Plain and Caucasus, Central Asia and the Caspian Region, Eastern and Southern Siberia, and the Far East.

The Arctic and Sub-Arctic. "The 9th-14th centuries were relatively warm, though at least two colder periods probably occurred in the 11th and 13th centuries," after which "the 15th-early 20th centuries were generally cold," and "subsequent warming is recorded with almost all proxies."

The Russian Plain and Caucasus. "The climate of the Russian plain was relatively warm from the 11th to 14th centuries, with the exception of the late 12th-early 13th centuries, and colder from the 15th to 19th centuries, except for a warm interval in the first half of the 16th century." In the Central Caucasus, they also report the existence of a "relatively warm climate around the end of the first to the beginning of the second millennium AD," followed by "numerous glacier advances ... during the 14th-19th centuries," the timing of which correlates well with glacier advances in the European Alps.

Central Asia and the Caspian Region. "A milder, less continental climate with more precipitation approximately from the 9th to 12th centuries" was indicated by most of the available data, and "cold conditions dominated from the 13th to 19th centuries, though interrupted by a brief warm period from the end of the 14th-early 15th century," after which "the coldest conditions were probably in the 17th and 19th centuries, when glaciers advanced several times, lake level was high, and permafrost depth increased."

Eastern and Southern Siberia. "Two periods of warmer and drier climate can be roughly identified in this huge area as having occurred from the 9th to 11th centuries and in the 14th century," and "the 15th-19th centuries were clearly cold and the 20th century has seen a return to warm conditions."

The Far East. "There is some evidence suggesting moderately warm conditions in the North Pacific region from the end of the first to the beginning of the second millennium," with "a subsequent cooling after the 14th century."

Summarizing their findings for the bulk of Northern Eurasia, Solomina and Alverson write, "a number of records allow one to distinguish the climatic pattern of the 9th-13th centuries [i.e., the Medieval Warm Period] from earlier and later colder conditions [i.e., the Dark Ages Cold Period and Little Ice Age, respectively]." They also note "the spatial pattern of temperature anomalies ca. 1000 years ago is similar to the earlier mid-Holocene 'optimum.'" They write, "the warming of the 14th century in several regions, including the Russian plain, Altai and Central Asia, was at least as intense as the earlier one at ca. 1000 years before present or even warmer." The latter widely detected event might correspond to what some have called the Little Medieval Warm Period, or it may be the final years of the Medieval Warm Period before it relinquished control of Earth's climate to the Little Ice Age.

Kalugin *et al*. (2005) analyzed sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia (51°42.90'N, 87°39.50'E), producing a multi-proxy climate record spanning the past 800 years. This record revealed several distinct climate periods over the past eight centuries. The regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, temperatures cooled, reaching peak deterioration between 1660 and 1700, which "corresponds to the age range of the well-known Maunder Minimum (1645–1715)" and is "in agreement with the timing of the Little Ice Age in Europe (1560–1850)." Recovery to prior-level warmth did not occur until late in the twentieth century.

With respect to moisture and precipitation, Kalugin *et al*. state the period between 1210 and 1480 was more humid than today, whereas the period between 1480 and 1840 was more arid. In addition, they report three episodes of multi-year drought (1580–1600, 1665–1690, and 1785–1810). These findings agree with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al*., 1996; Panyushkina *et al*., 2000). Their findings prove problematic for those who claim global warming will lead to more severe droughts, as all of the major multi-year droughts detected in this study occurred during the cool phase of the 800-year record.

Mackay *et al*. (2005) analyzed paleolimnological data obtained from a sediment core taken from the south basin of Lake Baikal, Russia, to reconstruct the climatic history of this area of central Asia over the past millennium. Their use of cluster analysis identified three significant zones of variability in the sediment core coincident with the Medieval Warm Period (c. 880 AD to c. 1180 AD), the Little Ice Age (c. 1180 AD to 1840 AD), and the Current Warm Period. The seven scientists say their diatom data supported the idea that "the period known as the MWP in the Lake Baikal region was a relatively warm one." Following the MWP, diatom species shifted toward taxa indicative of colder climates, implying maximum snow depth values during the Maunder Minimum (1645–1715 AD), after which the diatom-derived snow accumulation data indicated a warming trend in the Lake Baikal region that began as early as c. 1750 AD. That the warming began around 1750 AD, nearly 100 years before the modern rise in atmospheric CO_2 concentration, suggests the planet's current warmth is the result of nothing more than the most recent and expected upward swing of this natural climatic oscillation.

Mazepa (2005) notes "dead trees located above the current tree-line ecotone provide evidence of the dynamic behavior in the location of the tree line in the recent past (Shiyatov, 1993, 2003)" and "previous studies have concluded that increases in tree-line elevation, and associated increases in tree abundance within the transient tree-line ecotone, are associated with extended warm periods (Tranquillini, 1979; Kullman, 1986; Payette *et al*., 1989; Lloyde and Fastie, 2003; Lloyd *et al*., 2003; Grace *et al*., 2002; Helama *et al*., 2004)."

Mazepa evaluated the uniqueness of Polar Ural tree-line and density response "to what is widely considered to be anomalous 20th-century warming," examining evidence of tree growth dynamics along a continuous altitudinal transect 860 meters long and 40–80 meters wide on the eastern slope of the Polar Ural Mountains (66°48'57"N, 65°34'09"E) by repeating what Shiyatov had done four decades earlier. Mazepa discovered "a large number of well-preserved tree remains can be found up to 60–80 meters above the current tree line, some dating to as early as a maximum of 1300 years ago," and "the earliest distinct maximum in stand density occurred in the 11th to 13th centuries, coincident with Medieval climatic warming," when "summer air temperatures may have been 0.42–0.56°C warmer than they were over the last decades of the 20th century."

Andreev *et al*. (2007) analyzed pollen and charcoal stratigraphy in a sediment core extracted from the central and deepest part of Lake Teletskoye in the northeastern part of the Altai Mountains in southern Siberia (51°43'N, 87°39'E), developing what they describe as "the first detailed climate and vegetation reconstruction for the last millennium in the northern Altai Mountains" (see Figure 4.2.4.4.3.1).

They found "dense Siberian pine forest dominated the area around the lake at least since ca. AD 1020," when "climate conditions were similar to modern." Then, "between AD 1100 and 1200, a short dry period with increased fire activity occurred," and "around AD 1200, climate became more humid with the temperatures probably higher than today." This period of relatively stable climate, "possibly reflecting [the] Medieval Warm Epoch, lasted until AD 1410," after which "slightly drier climate

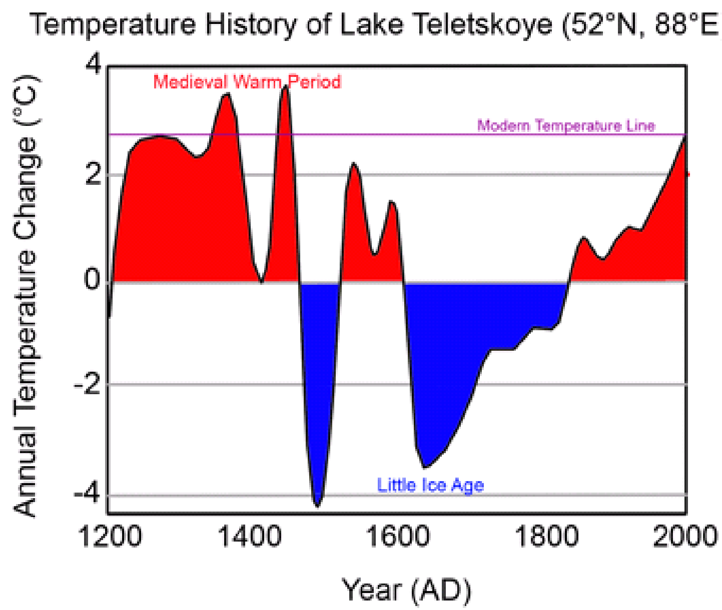

Figure 4.2.4.4.3.1. Proxy temperature record of Lake Teletskoye in the northeastern part of the Altai Mountains in southern Siberia. Adapted from Andreev, A.A., Pierau, R., Kalugin, I.A., Daryin, A.V., Smolyaninova, L.G., and Diekmann, B. 2007. Environmental changes in the northern Altai during the last millennium documented in Lake Teletskoye pollen record. *Quaternary Research* **67**: 394–399.

conditions occurred between AD 1410 and 1560." Thereafter, "a subsequent period with colder and more arid climate conditions between AD 1560 and 1820 is well correlated with the Little Ice Age," after which the evidence indicated a climate warming they "inferred from the uppermost pollen spectra, accumulated after AD 1840," which was "consistent with the instrumental data" of the modern period.

It is clear from Andreev *et al*.'s findings that the Altai Mountain region of southern Siberia displays the characteristic millennial-scale cycling of climate, from Medieval Warm Period to Little Ice Age to Current Warm Period conditions, that is characteristic of most of the rest of the world. That temperatures in the region from approximately AD 1200 to 1410 were "probably higher than today" provides yet another example of times and places when and where low-CO_2 Medieval Warm Period temperatures were likely higher than high-CO_2 Current Warm Period temperatures.

Kalugin *et al*. (2007) collected several sediment cores from the deepest area of Teletskoye Lake and measured the spectra of numerous elements—including Ba, Cd, Ce, I, La, Mo, Nb, Rb, Sb, Sn, Sr, Th, U, Y, and Zr—after which "artificial neural networks (Veelenturf, 1995) were used for reconstruction of annual temperature and precipitation by sediment properties (Smolyaninova *et al*., 2004)." The six scientists state, "a global cold period, the Little Ice Age with Maunder minimum, is clearly designated in their data, as well as global warming during the 19–20th centuries," implying the existence of the Medieval Warm Period that preceded the Little Ice Age. Their plot of the data (see Figure 4.2.4.4.3.2) shows the mean peak temperature of the latter part of the Medieval Warm Period was about 0.5°C higher than the mean peak temperature of the Current Warm Period, which occurred at the end of the record.

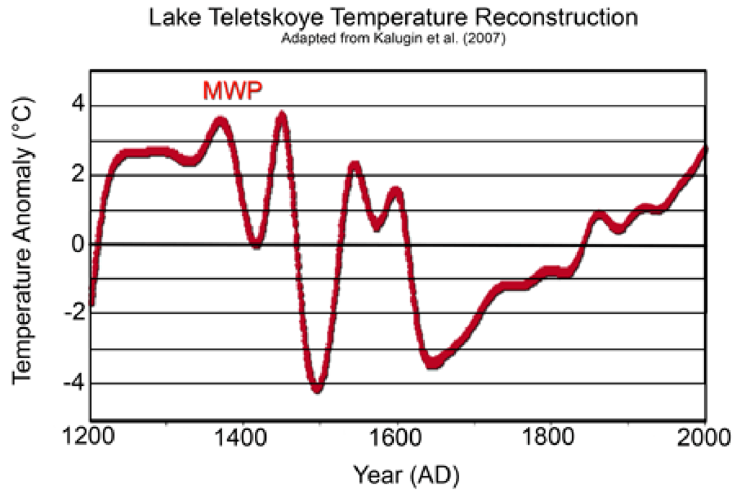

Figure 4.2.4.4.3.2. Proxy temperature record of Lake Teletskoye in the Altai Mountains in southern Siberia. Adapted from Kalugin, I., Daryin, A., Smolyaninova, L., Andreev, A., Diekmann, B., and Khlystov, O. 2007. 800-yr-long records of annual air temperature and precipitation over southern Siberia inferred from Teletskoye Lake sediments. *Quaternary Research* **67**: 400–410.

Matul *et al*. (2007) studied the distributions of siliceous microflora (diatoms), calcareous microfauna (foraminifers), and spore-pollen assemblages found in sediment cores retrieved from 21 sites on the inner shelf of the southern and eastern Laptev Sea, starting from the Lena River delta and moving seaward between about 130 and 134°E and stretching from approximately 71 to 78°N. The cores were acquired by a Russian-French Expedition during the cruise of R/V *Yakov Smirnitsky* in 1991. The research revealed, in the words of the five Russian scientists, "(1) the warming at the beginning of the Common Era (terminal epoch of the Roman Empire) during ~1600–1900 years BP; (2) the multiple, although low-amplitude, cooling episodes at the beginning of the Middle Ages, 1100–1600 years BP; (3) the Medieval Warm Period, ~600–1100 years BP; (4) the Little Ice Age, ~100–600 years BP, with the cooling maximum, ~150–450 years BP; and (5) the 'industrial' warming during the last 100 years." They conclude, "judging from the increased diversity and abundance of the benthic foraminifers, the appearance of moderately thermophilic diatom species, and the presence of forest tundra (instead of tundra) pollen, the Medieval warming exceeded the recent 'industrial' one."

Sidorova *et al*. (2007) developed a history of trunk radial growth increment of larch (*Larix gmelinii* Rupr.) trees in the middle reaches of the Bol'shoi Avam River on the northern edge of the Putoran Plateau, central Taimyr (70°30'N, 93°01'E), for the period AD 886–2003, which they found to be correlated with summer air temperature. This work revealed a period from the start of the record to approximately AD 1200 when inferred temperatures were generally much greater than those of the final decades of the twentieth century.

MacDonald *et al*. (2008) conducted an analysis of past changes in the location of the northern Russian treeline, as reconstructed from tree-ring data and radiocarbon-dated subfossil wood, to ascertain whether "the pattern of recent warming over the late nineteenth and the twentieth centuries caused significant changes in the density of trees at the treeline and/or an extension of the geographical location of the treeline." They report "temperature increases over the past century are already producing demonstrable changes in the population density of trees, but these changes have not yet generated an extension of conifer species' limits to or beyond the former positions occupied during the Medieval Warm Period (MWP: *ca* AD 800–1300) or the Holocene Thermal Maximum treeline extension (HTM: broadly taken here to be *ca* 10,,000–3,000 years ago)."

On the Khibiny uplands of the central Kola Peninsula, for example, "the treeline was located 100–140 m higher in elevation than today during the MWP," and "forest has yet to recolonize these elevations (Kremenetski *et al*., 2004).” Of the northern Polar Urals they state, “the treeline was at its highest elevation during the MWP between *ca* AD 900 and 1300 when it reached 340 m,” after which it “descended to approximately 270 m during the Little Ice Age and then ascended to its present elevation of approximately 310 m during the recent warming of the late nineteenth and twentieth centuries.”

The three researchers conclude, “at the Russian sites studied, the impact of twentieth century warming has not yet compensated fully for the mortality and range constriction caused by the cold temperatures of the Little Ice Age,” and they note “these results are similar to observations in some other northern treeline regions such as uplands in eastern Quebec and interior Labrador where *Picea mariana* (P. Mill.) B.S.P. and *Picea glauca* (Moench) Voss trees remain below their pre-Little Ice Age limits despite recent warming (Gamache and Payette, 2005; Payette, 2007).”

Noting the long-term decrease in seasonal peaks of water levels allows human settlement of low geomorphic locations, such as river and lake floodplains, whereas a rise in flood levels causes settlements to be shifted to higher elevations, Panin and Nefedov (2010) noted “ancient settlements could not persist under the impact of regular inundations.” In a study of the Upper Volga and Zapadnaya Dvina Rivers of Russia, the two researchers determined “the geomorphological and altitudinal positions of [human] occupational layers corresponding to 1224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province,” identifying “a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchical rank.”

They found “low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs,” because “during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in seasonal peaks in lake levels,” while noting “a model of past warming epochs can be the warming in the late 20th century.” They also report finding “in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays.” They found the period AD 1000–1300 hosted the greatest number of floodplain settlements..

Panin and Nefedov argue this last period and other “epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th-early current century,” which they say “is forming under the effect of directed climate change.” This relationship clearly implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

Noting dust storms are common features adjacent to the Aral Sea, Huang *et al*. (2011) investigated the grain-size distributions of wind-blown sediments found in a core retrieved from that water body while “attempting to trace the variations in atmospheric dynamics in central Asia during the past 2000 years,” They focused on variations observed at the transition from the Medieval Warm Period to the Little Ice Age, since this period, they write, “is the most pronounced climatic transformation during the last millennium,” citing Yang B. *et al*. (2002), Trouet *et al*. (2009), and Chen *et al*. (2010). Their analysis revealed the history of dust deposition in central Asia can be divided into five distinct periods on the basis of their observations: “a remarkably low deposition during AD 1–350, a moderately high value from AD 350–720, a return to a relatively low level between AD 720 and AD 1400 (including the Medieval Warm Period), an exceptionally high deposition from AD 1400 to [the] 1940s and an abnormally low value since [the] 1940s.”

The first of these “distinct periods” coincides with the Roman Warm Period, the second with the Dark Ages Cold Period, the third (as Huang *et al*. note) with the Medieval Warm Period, the fourth with the Little Ice Age, and the fifth with the Current Warm Period. They found the temporal variation in dust deposition they observed was consistent with the “mean atmospheric temperature of the Northern Hemisphere during the past 2000 years, with low/high annual temperature anomalies corresponding to high/low dust supplied in the Aral Sea sediments, respectively.” The four researchers’ graphs of their wind intensity/dust storm data show the minimum values of these inverted measures of annual temperature during the Roman Warm Period, the Medieval Warm Period, and the Current Warm Period were all about the same.

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4.2.4.4.4 Other Asian Countries

In addition to China, Russia, and Japan, the MWP has been identified in several other parts of Asia. Schilman *et al*. (2001), for example, analyzed foraminiferal oxygen and carbon isotopes, together with physical and geochemical properties of sediments, contained in two cores extracted from the bed of the southeastern Mediterranean Sea off the coast of Israel, where they found evidence for the MWP centered on AD 1200. They note there is an abundance of other well-documented evidence for the existence of the MWP in the Eastern Mediterranean, including, they write, "high Saharan lake levels (Schoell, 1978; Nicholson, 1980), high Dead Sea levels (Issar *et al*., 1989, 1991; Issar, 1990, 1998; Issar and Makover-Levin, 1996), and high levels of the Sea of Galilee (Frumkin *et al*., 1991; Issar and Makover-Levin, 1996)," in addition to "a precipitation maximum at the Nile headwaters (Bell and Menzel, 1972; Hassan, 1981; Ambrose and DeNiro, 1989) and in the northeastern Arabian Sea (von Rad *et al*., 1999)."

Schilman *et al*. (2002) analyzed high-resolution $\delta^{18}O$ values from a speleothem in Soreq Cave, central Israel (31°45'N, 35°03'E), as well as from planktonic foraminifera in two marine sediment cores retrieved just off the Ashdod coast (31°56.41'N, 34°22.13'E and 31°56.61'N, 34°19.79'E), to obtain a record of climate in this region over the past 3,600 years. The $\delta^{18}O$ values of the speleothem and marine cores showed "striking similarity" over the period of study, according to Schilman *et al*., and they were determined to be primarily representative of historic changes in precipitation. Over the 3,600-year record, six major precipitation intervals were noted, three that were relatively wet and three that were relatively dry. The peaks of the humid events occurred at 3,200, 1,300, and 700 yr BP, the latter of which was said by the researchers to be "associated with the global MWP humid event."

Cini Castagnoli *et al*. (2005) extracted a $\delta^{13}C$ profile of *Globigerinoides rubber* from a shallow-water core in the Gulf of Taranto (39°45'53"N, 17°53'33"E) to produce a high-precision record of climate variability over the past two millennia, after which it was statistically analyzed, together with a second two-millennia-long tree-ring record obtained from Japanese cedars (Kitagawa and Matsumoto, 1995), for evidence of recurring cycles using Singular Spectrum Analysis and Wavelet Transform. Plots of both records revealed the Dark Ages Cold Period (~400–800 AD), the Medieval Warm Period (~800–1200 AD), the Little Ice Age (~1500–1800 AD), and the Current Warm Period, the roots of which can be traced to an upswing in temperature that began in the depths of the Little Ice Age "about 1700 AD."

Both records were compared with a 300-year record of sunspots Results of the statistical analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity, plus a second multidecadal oscillation (of about 93 years for the shallow-water *G. rubber* series and 87 years for the tree-ring series) in phase with the amplitude modulation of the sunspot number series over the last 300 years. According to the three researchers, the overall phase agreement between the two climate reconstructions and the variations in the sunspot number series "favors the hypothesis that the [multidecadal] oscillation revealed in $\delta^{13}C$ from the two different environments is connected to the solar activity," suggesting a solar forcing was at work in both terrestrial and oceanic domains over the past two millennia.

Li *et al*. (2006) conducted palynological analyses of two sediment cores taken from the Song Hong (Red River) Delta, Vietnam (~20.26°N, 106.52°E) to reconstruct climate variations there throughout the Holocene. As indicated by an abundance of taxa well adapted to tropical and subtropical environments, they conclude the Medieval Warm Period (~AD 500–1330) was warmer than the current climate.

Kaniewski *et al*. (2011) write, "according to model-based projections, the northern Arabian Peninsula, a crossroad between Mediterranean, continental and subtropical climates, will be extremely sensitive to greenhouse warming," citing the work of Alpert *et al*. (2008). They also note, "insights into past climate variability during historical periods in such climate hotspots are of major interest to estimate if recent climate trends are atypical or not over the last millennium," but "few palaeo-environmental records span the MCA [Medieval Climate Anomaly] and LIA [Little Ice Age] in the Middle East." Based on an analysis of pollen types and quantities found in a 315-cm sediment core retrieved from alluvial deposits within the floodplain of a spring-fed valley located at 35°22'13.16"N, 35°56'11.36"E in the coastal Syrian lowland, Kaniewski *et al*. converted the pollen data into Plant Functional Types (PFTs) that allowed them to construct pollen-derived Biomes (PdBs) similar to the regional studies of Tarasov *et al*. (1998). They were then able to relate the ratio of PdB warm steppe (WAST) divided by PdB cool steppe (COST) to local temperature, as also had been done a decade earlier by Tarasov *et al*. (1998).

The seven scientists state their WAST/COST record "indicates that temperature changes in coastal Syria are coherent with the widely documented warming during the MCA and cooling during the LIA," assigning the first of these epochs to the period of approximately AD 1000 to 1230 and the latter to approximately AD 1580 to 1850. Regarding the Current Warm Period, they state, "modern warming appears exceptional in the context of the past 1250 years, since only three warm peaks of similar amplitude are registered during the High Middle Ages." However, they conclude, the "three peaks centered on ca. 1115, 1130 and 1170 cal yr AD suggest similar or warmer temperatures compared to AD 2000." The plot of their WAST/COST record (Figure 4.2.4.4.4.1) shows the warmth of the first and last of these peaks was essentially identical to that centered on the end of the last century (AD 2000), and the central peak at AD 1130 was the warmest..

The findings of Kaniewski *et al.* thus reveal recent climate trends in the region of Syria they studied are not atypical over the last millennium, although they do not say so in their study. Earth's current level of warmth need not be attributed to the current high level of the air's CO_2 content; the peak warmth of the MWP was greater than it has been over the past couple of decades yet the air's CO_2 concentration was approximately 100 ppm less than it is today.

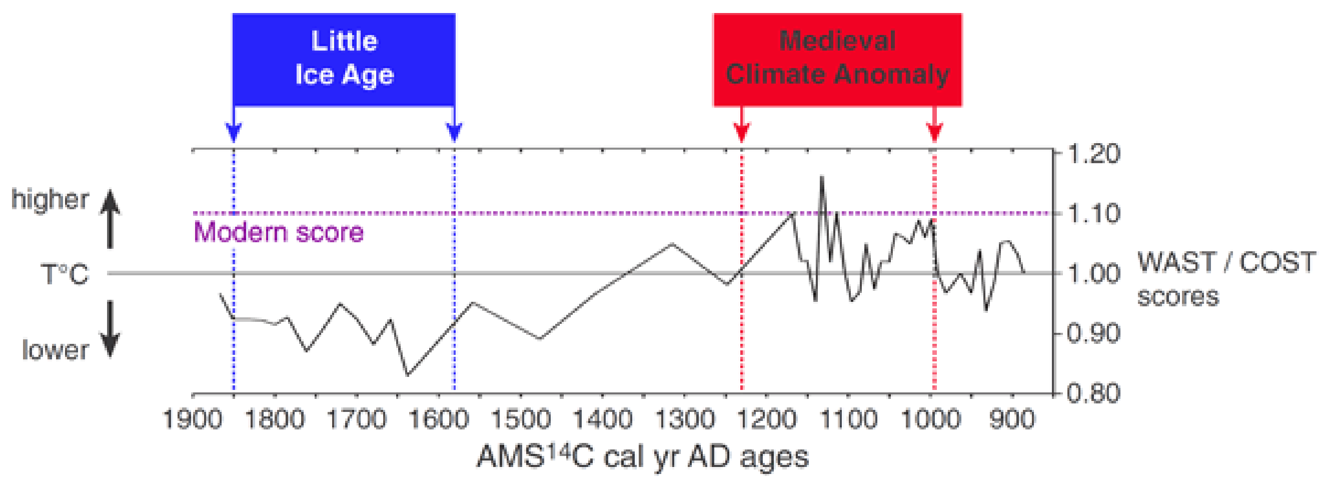

Figure 4.2.4.4.4.1. The 880-1870 cal yr AD warm-cool ratio WAST/COST temperature reconstruction of Kaniewski, D., Van Campo, E., Paulissen, E., Weiss, H., Bakker, J., Rossignol, I., and Van Lerberghe, K. 2011. The medieval climate anomaly and the little Ice Age in coastal Syria inferred from pollen-derived palaeoclimatic patterns. *Global and Planetary Change* **78**: 178–187, Figure 5.

Kar *et al.* (2002) explored the nature of climate change in India as preserved in the sediment profile of an outwash plain two to three km from the snout of the Gangotri Glacier in the Uttarkashi district of Uttranchal, Western Himalaya. Their data reveal a relatively cool climate between 2,000 and 1,700 years ago. From 1,700 to 850 years ago, there was what they called an "amelioration of climate" during the transition from the depth of the Dark Ages Cold Period to the midst of the Medieval Warm Period. After that, Kar *et al.*'s data indicate the climate "became much cooler," indicative of its transition to Little Ice Age conditions, and during the last 200 years there has been a rather steady warming, as shown by Esper *et al.* (2002a) to have been characteristic of the entire Northern Hemisphere.

Feng and Hu (2005) acquired decadal surface air temperatures for the last two millennia from ice core and tree-ring data obtained at five locations on the Tibetan Plateau. These data revealed the late twentieth century was the warmest period in the past two millennia at two of the sites (Dasuopu, ice core; Dunde, ice core), but not at the other three sites (Dulan, tree ring; South Tibetan Plateau, tree ring; Guilya, ice core). At Guilya, for example, the data indicated it was significantly cooler in the final two decades of the twentieth century than for most of the first two centuries of the record, which comprised the latter part of the Roman Warm Period. At the South Tibetan Plateau it was also significantly warmer over a full century near the start of the record, and at Dulan it was significantly warmer for the same portion of the Roman Warm Period plus two near-century-long portions of the Medieval Warm Period. These observations cast doubt on claims late twentieth century temperatures were unprecedented over the past two millennia, and they provide additional evidence for the millennial-scale climatic oscillation that sequentially brought the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period.

Phadtare and Pant (2006) developed a 3,500-year palaeoclimate record of the Late Holocene using a study of pollen and organic matter content and the magnetic susceptibility of radiocarbon-dated samples from a peat deposit in the Kumaon Higher Himalaya of India (30°3'N, 70°56'E). "With an abrupt rise in temperature as well as moisture at ~AD 400," they write, "the climate suddenly turned warm and moist and remained so until ~AD 1260." This period, they note, is "generally referred to as the Medieval Warm Period in the Northern Hemisphere." The climate turned cold and dry over the ensuing century, but then warm and wet again, before turning "cold and moist during ~AD 1540–1730," stating the latter climate episode "represent[s] the Little Ice Age event in the Garhwal-Kumaon Himalaya."

Thereafter, the Indian researchers say, "the climate has been persistently wet with relatively higher temperatures until ca. AD 1940, followed by a cooling trend that continued till the present."

This dramatic modern cooling also is observed in the regional tree-ring record of Yadav *et al*. (2004), who used many long tree-ring series obtained from widely spaced Himalayan cedar (*Cedrus deodara* (Roxb.) G. Don) trees growing on steep slopes with thin soil cover to develop a temperature history of the western Himalayas for the period AD 1226–2000. "Since the 16th century," they write, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226–1500), reflecting unstable climate during the Little Ice Age (LIA)."

Yadav *et al*. note similar results have been obtained from juniper tree-ring chronologies from central Tibet (Braeuning, 2001), and "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." Yadav *et al*. report 1944–1953 was the warmest 10-year mean of the entire 775-year record, and "thereafter, temperatures decreased." This cooling, they note, "is in agreement with the instrumental records." Also, they state, "tree-ring based temperature reconstructions from other Asian mountain regions like Nepal (Cook *et al*., 2003), Tibet and central Asia (Briffa *et al*., 2001) also document cooling during [the] last decades of the 20th century."

The temperatures of the final two decades of Yadav *et al*.'s record appear to be as cold as those of any comparable period over the prior seven-and-a-half centuries, including the coldest periods of the Little Ice Age. This result, they indicate, is radically different from the temperature reconstruction of Mann and Jones (2003), which depicts "unprecedented warming in the 20th century."

Brauning and Griessinger (2006) analyzed $\delta^{13}C$ data obtained from wood cellulose of annual growth rings of long-lived juniper (*Juniperus tibetica*) trees growing at a site in east-central Tibet at approximately 31.8°N, 92.4°E, which were found to be significantly positively correlated with summer temperatures of the surrounding region. The authors found "warm and dry conditions during the Medieval Warm Period between AD 1200 and 1400." Their graph of the data reveals the peak temperature of the MWP to have been greater than the peak temperature of the CWP.

Chauhan (2006) derived abundance distributions of various types of pollen deposited over the past 1,300 years in a one-meter-deep sediment core retrieved from the alpine-region Naychhudwari Bog (77°43'E, 32°30'N) of Himachal Pradesh, northern India. Analyses revealed two broad climatic episodes of warm-moist and cold-dry conditions, the first covering the period AD 650 to 1200 and the second from AD 1500 onwards. "In the global perspective," the Indian scientist writes, the first period "is equivalent to the Medieval Warm Period, which has been witnessed in most parts of the world," while the second period "falls within the time-limit of [the] Little Ice Age."

In the first of these two periods, Chauhan remarks, "the alpine belt of this region experienced warm and moist climate [and] the glaciers receded and the tree-line ascended to higher elevations," suggesting the existence of a prior cooler and drier climate, the Dark Ages Cold Period. From AD 1500 onward, Chauhan writes, "the glaciers advanced and consequently the tree-line descended under the impact of [the] cold and dry climate in the region."

Bhattacharyya *et al*. (2007) developed a relative history of atmospheric warmth and moisture covering the last 1,800 years for the region surrounding Paradise Lake, located in the Northeastern Himalaya at approximately 27°30.324'N, 92°06.269'E, based on pollen and carbon isotopic ($\delta^{13}C$) analyses of a one-meter-long sediment profile obtained from a pit "dug along the dry bed of the lakeshore." Their climatic reconstruction revealed a "warm and moist climate, similar to the prevailing present-day conditions," around AD 240, which would represent the last part of the Roman Warm Period, and another such period "warmer 1100 yrs BP (around AD 985) corresponding to the Medieval Warm Period."

Chauhan and Quamar (2010) analyzed a 2-m-long sediment core retrieved from the Kiktiha Swamp of Central India (~23°N, 84°E) to develop temporal distributions of many types of plants, identifying three major climatic regimes over the past 1,650 years. The first of these regimes was described by the two researchers as "a warm and moist climate," which "supported tropical deciduous Sal forests." This interval "corresponds with the period of the Medieval Warm Period, which is known between AD 740 and 1150 (Lamb, 1977)." The second regime, from about AD 1250 to 1650, was mostly a "period of harsh climate" that "falls within the temporal range of [the] Little Ice Age." It was followed by the third regime, another warm period that has now persisted for three centuries and resulted in "the revival of modern Sal forests." It is not possible to determine from Chauhan and Quamar's paper which of the two warm periods may have been the warmer.

Kotlia and Joshi (2013) examined a 3.55-meter-long sediment core extracted from Badanital Lake (30°29'50"N, 78°55'26"E) in the Garhwal Himalaya of India, finding "the imprints of four major global events"—the "4.2 ka event, Medieval Warm Period (MWP), Little Ice Age (LIA) and modern warming"—based on measurements and analyses of "major oxides and their ratios (CaO/MgO, CaO/TiO2, MgO/TiO2, Na2O/TiO2, TiO2/Al2O3, Na2O/K2O and Fe2O3/TiO2), major elements, chemical index of weathering, chemical index of alteration and loss on ignition." They report the MWP "prevailed around 920–440 years BP," concluding their work "adds to the growing evidence for the global extent of these events."

Esper *et al*. (2002b) used more than 200,000 ring-width measurements obtained from 384 trees at 20 sites ranging from the lower to upper timberline in the Northwest Karakorum of Pakistan (35–37°N, 74–76°E) and Southern Tien Shan of Kirghizia (40°10'N, 72°35'E) to reconstruct regional patterns of climatic variations in Western Central Asia since AD 618. They found the Medieval Warm Period was firmly established and growing warmer by the early seventh century, and between AD 900 and 1000, tree growth was exceptionally rapid, at rates they say "cannot be observed during any other period of the last millennium."

Between AD 1000 and 1200, growing conditions deteriorated, and at about 1500, minimum tree ring-widths were reached that persisted well into the seventeenth century. Toward the end of the twentieth century, ring-widths increased once again, but Esper *et al*. (2002b) report "the twentieth-century trend does not approach the AD 1000 maximum." There is almost no comparison between the two periods, with the Medieval Warm Period being far more conducive to tree growth than the Current Warm Period. As the three researchers note, "growing conditions in the twentieth century exceed the long-term average, but the amplitude of this trend is not comparable to the conditions around AD 1000."

Esper *et al*. (2003) processed several extremely long juniper ring width chronologies for the Alai Range of the western Tien Shan in Kirghizia in such a way as to preserve multi-centennial growth trends typically "lost during the processes of tree ring data standardization and chronology building (Cook and Kairiukstis, 1990; Fritts, 1976)." They used two techniques that maintained low frequency signals: long-term mean standardization (LTM) and regional curve standardization (RCS), as well as the more conventional spline standardization (SPL) technique that obscures (removes) long-term trends.

Carried back a full thousand years, the SPL chronologies depict significant interdecadal variations but no longer-term trends. The LTM and RCS chronologies, on the other hand, show long-term decreasing trends from the start of the record until about AD 1600, broad minima from 1600 to 1800, and long-term increasing trends from about 1800 to the present. Esper *et al*. (2003) report, "the main feature of the LTM and RCS Alai Range chronologies is a multi-centennial wave with high values towards both ends."

This result has essentially the same form as the Northern Hemisphere extratropical temperature history of Esper *et al*. (2002a), depicting the existence of both the Little Ice Age and preceding Medieval Warm Period, which are nowhere to be found in the "hockey stick" temperature reconstructions of Mann *et al*. (1998, 1999) and Mann and Jones (2003). In addition, the work of Esper *et al.* (2002b)—especially the LTM chronology, which has a much smaller variance than the RCS chronology—depicts several periods in the first half of the last millennium that were warmer than any part of the last century. These periods include much of the latter half of the Medieval Warm Period and a good part of the first half of the fifteenth century, which also has been found to have been warmer than it is currently by McIntyre and McKitrick (2003) and by Loehle (2004). Esper *et al*. (2003) remark, "if the tree ring reconstruction had been developed using 'standard' detrending procedures only, it would have been limited to inter-decadal scale variation and would have missed some of the common low frequency signal."

Treydte *et al*. (2009) write "it is still uncertain whether the magnitude and rate of 20th century warming exceeds natural climate variability over the last millennium," citing Esper *et al*. (2002a, 2005a, 2005b), Moberg *et al*. (2005), D'Arrigo *et al*. (2006), Frank *et al*. (2007), and Juckes *et al*. (2007). They developed "a millennium-long (AD 828–1998), annually resolved $\delta^{13}C$ tree-ring chronology from high-elevation juniper trees in northern Pakistan [35.74–36.37°N, 74.56–74.99°W] together with three centennial-long (AD 1900–1998) $\delta^{13}C$ chronologies from ecologically varying sites," defining an "optimum correction factor" they deemed best-suited to remove non-climatic trends in order to "provide new regional temperature reconstructions derived from tree-ring $\delta^{13}C$, and compare those records with existing regional evidence."

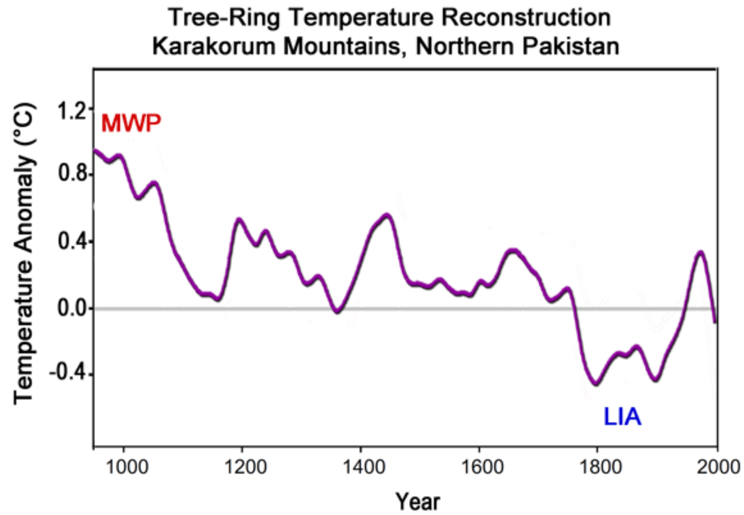

Figure 4.2.4.4.4.2. Proxy tree-ring temperature reconstruction from the Karakorum Mountains, Northern Pakistan. Adapted from Treydte, K.S., Frank, D.C., Saurer, M., Helle, G., Schleser, G.H., and Esper, J. 2009. Impact of climate and CO2 on a millennium-long tree-ring carbon isotope record. *Geochimica et Cosmochimica Acta* **73**: 4635–4647.

This analysis (see Figure 4.2.4.4.4.2) shows the 1990s were "substantially below MWP temperatures," and their reconstruction "provides additional suggestions that High Asian temperatures during the MWP might have exceeded recent conditions," which is also suggested by "ring-width data from living trees (Esper *et al*., 2007)." Thus they "find indications for warmth during the Medieval Warm Period" that imply summer temperatures "higher than today's mean summer temperature."

Yoshioka *et al*. (2001) analyzed the carbon isotopic composition of sediment cores taken from the Dae-Am San high moor (38.22°N, 128.12°E), located on the north-facing slope of Mount Dae-Am, Korean Peninsula. They found upward increases in the $\delta^{13}C$ of organic carbon in the sediment core, reaching a maximum at around AD 1100. These findings, according to the authors, suggest the climate of the Korean Peninsula was "warm during the Medieval Warm Period," adding, if their interpretation is correct, the Medieval Warm Period was likely a global event.

Park (2011) writes, "information produced by climate modeling has become progressively more important to understand past climate changes as well as to predict future climates." The Korean researcher also observes, "to evaluate the reliability of such climate model results, quantitative paleoclimate data are essential." In a study designed to obtain such data for a part of the world that has not been intensively studied, Park used modern surface pollen samples from the mountains along the east coast of Korea to derive pollen-temperature transfer functions, which were tested for robustness via detrended correspondence analysis and detrended canonical correspondence analysis, after which the best of these transfer functions was applied to the five fossil pollen records of Jo (1979), Chang and Kim (1982), Chang *et al*. (1987), Fuiki and Yasuda (2004), and Yoon *et al*. (2008), which were derived from four coastal lagoons of Korea's east coast plus one high-altitude peat bog.

Park determined "the 'Medieval Warm Period', 'Little Ice Age' and 'Migration Period' were clearly shown," the first of which was identified as having occurred between AD 700 and 1200, the next between AD 1200 and 1700, and the last as having occurred between AD 350 and 700. The earliest of these periods is commonly referred to as the Dark Ages Cold Period but sometimes described as the Migration Period, as Park reports it was a time "when people migrated southward in Europe because of deteriorating environmental conditions." The graphical representation of Park's temperature reconstruction shows the peak temperature of the Medieval Warm Period was only slightly lower (by about 0.18°C) than the peak temperature of the Current Warm Period, which occurs at the end of the Korean temperature record.

Park's findings imply "the various late-Holocene climate shifts all occurred in the Korean peninsula at the same time as in other regions of the world," and modern-day warming on the Korean peninsula is only slightly greater than what occurred there in the Medieval Warm Period. It is evident from Park's temperature reconstruction that it may have been slightly warmer approximately 2,200 years ago than it was near the end of the twentieth century, suggesting there is nothing unusual or unnatural about Earth's current level of warmth.

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4.2.4.5 Australia and New Zealand

Numerous peer-reviewed studies reveal modern temperatures are not unusual, unnatural, or unprecedented. Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration for many millennia. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 concentration remained at values approximately 30% lower than those of today.

This section highlights evidence from Australia and New Zealand, where much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; the Current Warm Period is simply a manifestation of its latest phase. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

Wilson *et al*. (1979) sought to compare the temperature record from New Zealand, which is "in the Southern Hemisphere and … meteorologically unrelated to Europe," with the climate record of England, where the MWP had been identified. They analyzed the $^{18}O/^{16}O$ profile from the core to the surface of a stalagmite obtained from a cave in New Zealand dated by the ^{14}C method. They found the proxy temperature record provided by the stalagmite was broadly similar to the climate record of England, exhibiting a period in the early part of the past millennium about 0.75°C warmer than it was in the mid-twentieth century (see Figure 4.2.4.5.1). They conclude, "such climatic fluctuations as the Medieval Warm Period and Little Ice Age are not just a local European phenomenon."

Eden and Page (1998) analyzed sediment cores from Lake Tutira, North Island, New Zealand (~39.23°S, 176.9°E) to reconstruct a history of major storms over the past 2,000 years. They found six well-defined and "clearly distinguishable" storm periods of

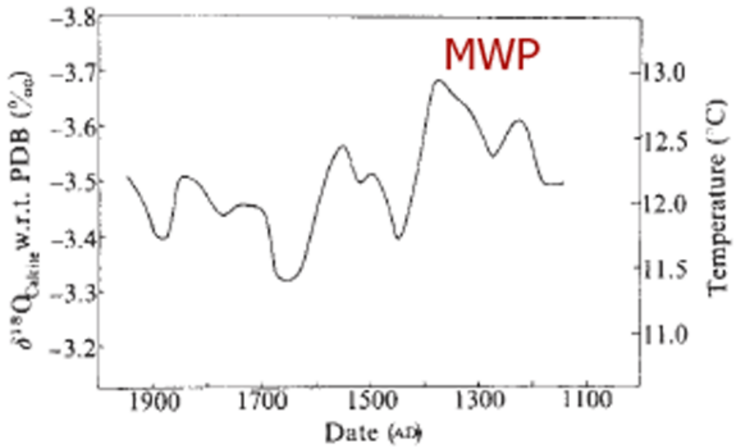

Figure 4.2.4.5.1. Proxy $^{18}O/^{16}O$ temperature reconstruction from a stalagmite in New Zealand. Adapted from Wilson, A.T., Hendy, C.H., and Reynolds, C.P. 1979. Short-term climate change and New Zealand temperatures during the last millennium. *Nature* **279**: 315–317.

the pre-instrumental era, illustrated in Figure 4.2.4.5.2. A seventh period based on data presented in Table 1 of the authors' paper has been added to indicate comparable storms of the modern era.

A comparison of these data with several independent climate proxies throughout the region led the authors to conclude stormy periods occurred during times when the climate was warmer overall. They note, "the Mapara 2 period corresponds to sustained warm temperatures in the Tasmanian and Chilean tree-ring records which might indicate that the period represents a Southern Hemisphere-wide climate anomaly." Additionally, "the Tufa Trig 1 period [AD 864–1014] corresponds to the early part of the Medieval Warm Period suggesting warmer temperatures occurred in New Zealand at this time." Similar correlations were noted among the other storm periods, leading to the inference that given the large number of storm events during the RWP and MWP, as compared to the Current Warm Period (CWP), it is likely the CWP has been neither as warm nor as protracted as these earlier warm periods.

Williams *et al*. (2004) revise and build upon results derived by Williams *et al*. (1999) from stable isotope stratigraphy found in caves at Waitomo, located at 38.3°S latitude about 35 km from the west coast of the central North Island of New Zealand. They enhanced three existing speleothem (stalactite, stalagmite, or flowstone cave deposit) records "by adding another chronology, increasing the subsample resolution of existing

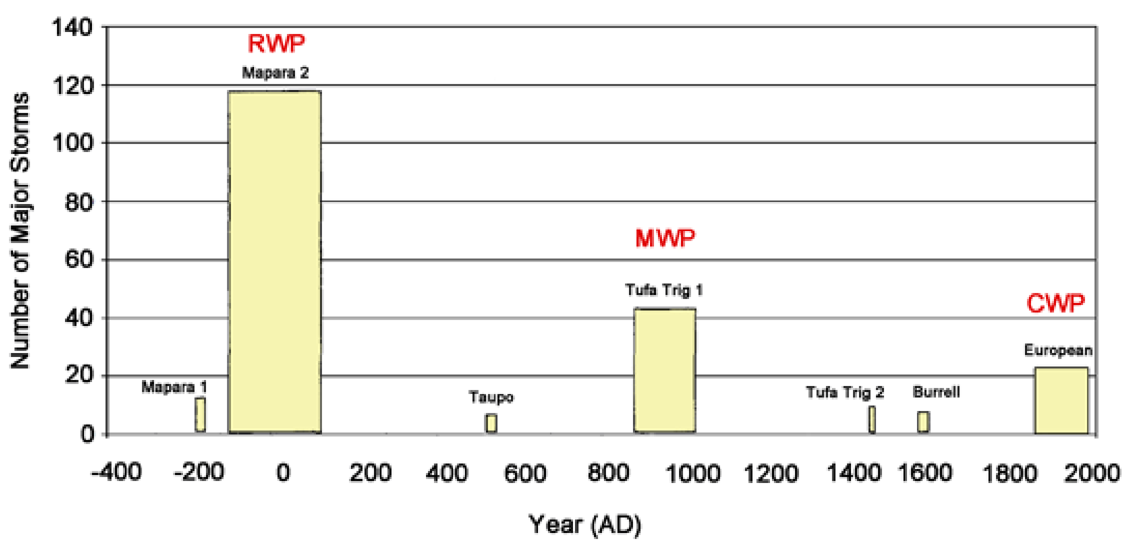

Figure 4.2.4.5.2. Number of major storms as determined from a sediment core from Lake Tutira, North Island, New Zealand. Adapted from Eden, D.N and Page, M.J. 1998. Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. *Palaeo-geography, Palaeoclimatology, Palaeoecology* **139**: 37–58.

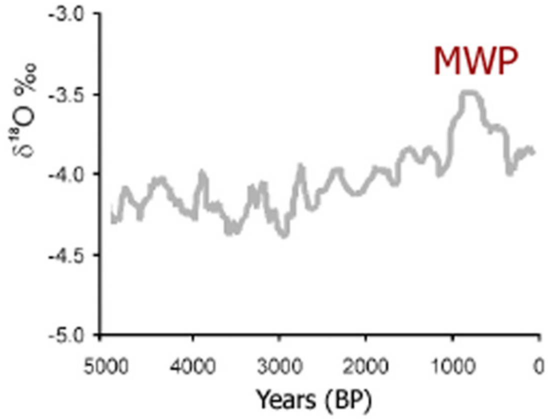

Figure 4.2.4.5.3. Composite $\delta^{18}O$ series obtained from four stalagmites found in caves at Waitomo, New Zealand. Adapted from Williams, P.W., King, D.N.T., Zhao, J.-X., and Collerson, K.D. 2004. Speleothem master chronologies: combined Holocene ^{18}O and ^{13}C records from the North Island of New Zealand and their palaeo-environmental interpretation. *The Holocene* **14**: 194–208.

records, and by much improving the temporal control of all chronologies by basing it entirely on uranium series TIMS dating." Williams *et al*.'s improved speleothem master chronologies revealed a warmer-than-present late-Holocene warm peak located between 0.9 and 0.6 ka BP (see Figure 4.2.4.5.3), which they equated with the Medieval Warm Period of Europe, further noting this period "coincided with a period of Polynesian settlement (McGlone and Wilmshurst, 1999)." Thereafter, they report, temperatures "cooled rapidly to a trough about 325 years ago," which they say corresponded to "the culmination of the 'Little Ice Age' in Europe."

Lorrey *et al*. (2008) developed two master speleothem $\delta^{18}O$ records for New Zealand's eastern North Island (ENI) and western South Island (WSI) for the period 2000 BC to about AD 1660 and 1825, respectively (see Figure 4.2.4.5.4). The WSI record was a composite chronology composed of data derived from four speleothems from Aurora, Calcite, Doubtful Xanadu, and Waiau caves, while the ENI record was a composite history derived from three speleothems from Disbelief and Te Reinga caves. For both the ENI and WSI $\delta^{18}O$ master speleothem histories, their warmest periods fell within the AD 900-1100 time interval of the MWP.

Wirrmann *et al*. (2011) developed a multi-proxy approach to climate in New Caledonia in the southwest tropical Pacific, determining between *ca.* 2,640 and 2,000 cal yr BP, conditions were "drier and cooler," and subsequent observations linked wetter with warmer. They report, "between ca. 1250–500 cal yr BP the higher % of Rhizophoraceae and their peak around ca. 1080–750 cal yr BP underscore a mangrove belt development along the coastline." This episode, they write, must be related to a wetter period and "may be related to a more global phenomenon such as the MWP in the Northern Hemisphere."

The IPCC has rejected the existence of a global MWP, suggesting it was mostly limited in scope to countries surrounding the North Atlantic Ocean. The studies described above are of great importance to the ongoing global warming debate because they provide evidence the the MWP was a global phenomenon in which temperatures around the world were significantly warmer than they have been at any time subsequently. These studies confirm there is nothing unusual or unprecedented about Earth's current level of warmth, with the necessary implication that the temperatures of the present cannot be attributed to the historical increase in the air's CO_2 content.

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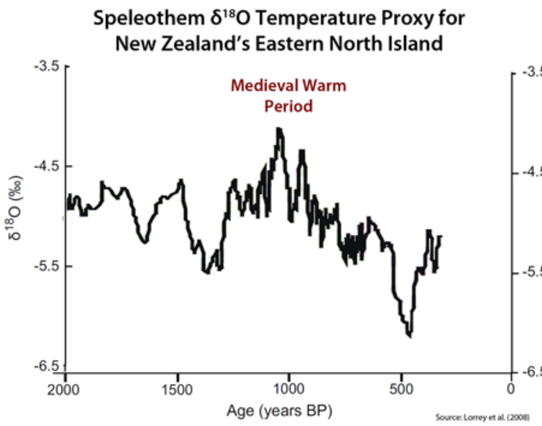

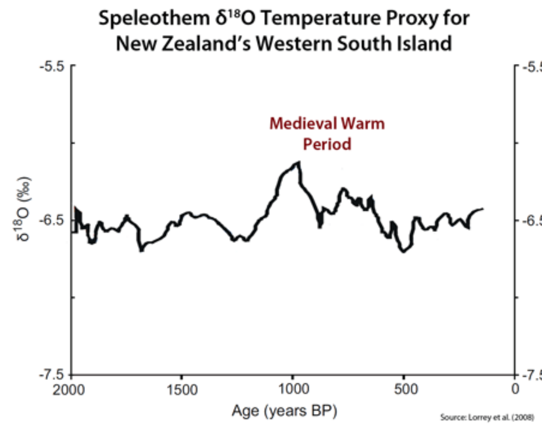

Figure 4.2.4.5.4. Composite speleothem $\delta^{18}O$ series obtained for New Zealand's eastern North Island and western South Island. Adapted from Lorrey, A., Williams, P., Salinger, J., Martin, T., Palmer, J., Fowler, A., Zhao, J.-X., and Neil, H. 2008. Speleothem stable isotope records interpreted within a multi-proxy framework and implications for New Zealand palaeoclimate reconstruction. *Quaternary International* **187**: 52–75.

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4.2.4.6 Europe

The following subsections highlight evidence from Europe showing conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO2 concentration remained at values approximately 30 percent lower than they are today. Much of the material here focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing independent of carbon dioxide levels. The Current Warm Period is simply a manifestation of its latest phase.

4.2.4.6.1 Central

Filippi *et al*. (1999) obtained stable isotope data (delta ^{18}O and delta ^{13}C) from bulk carbonate and ostracode calcite in a radiocarbon-dated sediment core removed from Lake Neuchatel in the western Swiss Lowlands at the foot of the Jura Mountains, which they used to reconstruct the climatic history of that region over the past 1,500 years (Figure 4.2.4.6.1.1). They determined mean annual air temperature dropped by about 1.5°C during the transition from the Medieval Warm Period (MWP) to the Little Ice Age (LIA). In addition, they state, "the warming during the 20th century does not seem to have fully compensated the cooling at the MWP-LIA transition" and during the Medieval Warm Period, mean annual air temperatures were "on average higher than at present."

Bodri and Cermak (1999) derived individual

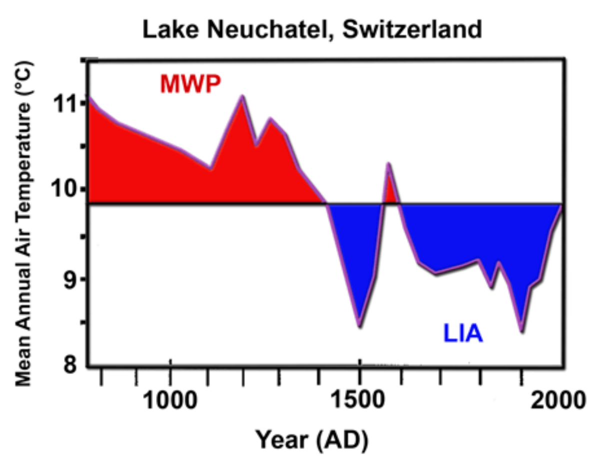

Figure 4.2.4.6.1.1. Temperature reconstruction obtained from sediment core removed from Lake Neuchatel in the western Swiss Lowlands. Adapted from Filippi, M.L., Lambert, P., Hunziker, J., Kubler, B., and Bernasconi, S. 1999. Climatic and anthropogenic influence on the stable isotope record from bulk carbonates and ostracodes in Lake Neuchatel, Switzerland, during the last two millennia. *Journal of Paleolimnology* **21**: 19–34.

ground surface temperature histories from the temperature-depth logs of 98 boreholes in the Czech Republic. This work revealed, they write, "the existence of a medieval warm epoch lasting from 1100–1300 AD," which they describe as "one of the warmest postglacial times." They also note during the main phase of the Little Ice Age, from 1600–1700 AD, "all investigated territory was already subjected to massive cooling," and "the observed recent warming may thus be easily a natural return of climate from the previous colder conditions back to a 'normal.'"

Niggemann *et al*. (2003) studied petrographical and geochemical properties of three stalagmites found in the B7-Cave of Sauerland, Northwest Germany, from which they developed a climate history for the prior 17,600 years. These records, they write, "resemble records from an Irish stalagmite (McDermott *et al*., 1999)," which also has been described by McDermott *et al*. (2001). The four researchers explicitly note their own records provide evidence for the existence of the Little Ice Age, the Medieval Warm Period, and the Roman Warm Period, which also implies the existence of what McDermott *et al*. (2001) called the Dark Ages Cold Period that separated the Medieval and Roman Warm Periods, as well as the unnamed cold period that preceded the Roman Warm Period. The wealth of corroborative information in these records (and many others) clearly suggests there is nothing unusual, unprecedented, or unexpected about the twentieth century warming that ushered in the Current Warm Period.

Bartholy *et al*. (2004) describe the work of Antal Rethly (1879–1975), a meteorologist, professor, and director of the National Meteorological and Earth Magnetism Institute of Hungary, who spent the greater portion of his long professional career collecting more than 14,000 historical records related to the climate of the Carpathian Basin. Rethly published in Hungarian a four-volume set of books, approximately 2,500 pages total, describing those records (Rethly, 1962, 1970; Rethly and Simon, 1999). Building upon this immense foundation, Bartholy *et al*. codified and analyzed the records collected by Rethly, noting, "in order to provide regional climate scenarios for any particular area, past climate tendencies and climatological extremes must be analyzed." The three Hungarian scientists report "the warm peaks of the Medieval Warm Epoch and colder climate of the Little Ice Age followed by the recovery warming period can be detected in the reconstructed temperature index time series."

Mangini *et al*. (2005) developed a highly resolved record of temperature at high elevation, approximately 2,500 meters above sea level, during the past 2,000 years, using a precisely dated $\delta^{18}O$ record with better than decadal resolution derived from a stalagmite recovered from Spannagel Cave in the Central Alps of Austria. They applied to the data a transfer function they derived from a comparison of their $\delta^{18}O$ data with the reconstructed temperature history of post-1500 Europe developed by Luterbacher *et al*. (2004).

Mangini *et al*. found the lowest temperatures of the past two millennia, according to the new record, occurred during the Little Ice Age (AD 1400–1850), and the highest temperatures were found in the Medieval Warm Period (MWP: AD 800–1300). They write, the highest temperatures of the MWP were "slightly higher than those of the top section of the stalagmite (1950 AD) and higher than the present-day temperature." At three points during the MWP, their data indicate temperature spikes in excess of 1°C above present (1995–1998) temperatures (see Figure 4.2.4.6.1.2).

Mangini *et al*. also report their temperature reconstruction compares well with reconstructions developed from Greenland ice cores (Muller and Gordon, 2000), Bermuda Rise ocean-bottom sediments (Keigwin, 1996), and glacier tongue advances and retreats in the Alps (Holzhauser, 1997; Wanner *et al*., 2000), as well as with the Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005). Considered together, Mangini *et al*. say the datasets "indicate that the MWP was a climatically distinct period in the Northern Hemisphere," emphasizing "this conclusion is in strong contradiction to the temperature reconstruction by the IPCC, which only sees the last 100 years as a period of increased temperature during the last 2000 years."

In a second refutation of an IPCC conclusion, Mangini *et al.* found "a high correlation between $\delta^{18}O$ and $\delta^{14}C$, that reflects the amount of radiocarbon in the upper atmosphere," and this correlation "suggests that solar variability was a major driver of climate in Central Europe during the past 2 millennia." They further report, "the maxima of $\delta^{18}O$ coincide with solar minima (Dalton, Maunder, Sporer, Wolf, as well as with minima at around AD 700, 500 and 300)," and "the coldest period between 1688 and 1698 coincided with the Maunder Minimum." Also, in a linear-model analysis of the percent of variance of their full temperature reconstruction that is

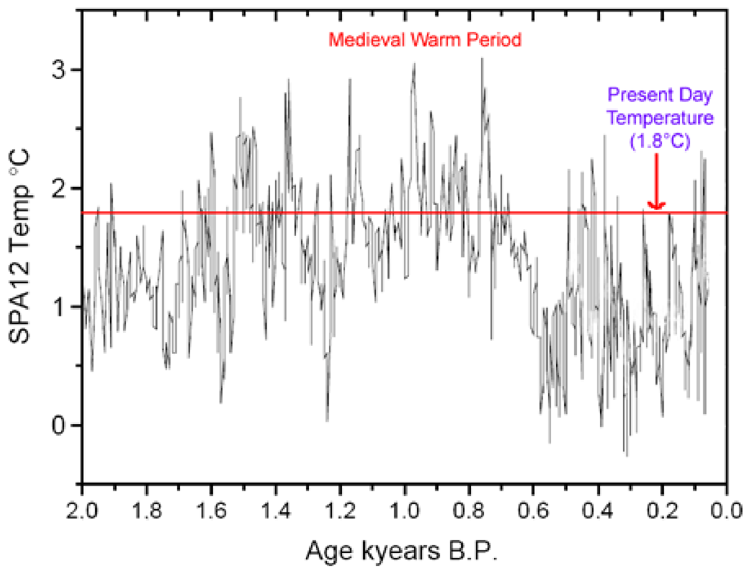

Figure 4.2.4.6.1.2. Temperature reconstruction from Spannagel Cave in the Central Alps of Austria. Adapted from Mangini, A., Spotl, C., and Verdes, P. 2005. Reconstruction of temperature in the Central Alps during the past 2000 yr from a $\delta^{18}O$ stalagmite record. *Earth and Planetary Science Letters* **235**: 741–751.

individually explained by solar and CO_2 forcing, they found the impact of the Sun was fully 279 times greater than that of the air's CO_2 concentration, noting "the flat evolution of CO_2 during the first 19 centuries yields almost vanishing correlation coefficients with the temperature reconstructions."

These findings show the hockey stick temperature reconstruction of Mann *et al.* (1998, 1999), which has long been endorsed by the IPCC, does not reflect the true temperature history of the Northern Hemisphere over the past thousand years, nor does the hockey stick temperature reconstruction of Mann and Jones (2003) reflect the true temperature history of the world over the past two millennia. The Mann studies and the IPCC appear to be focusing on the wrong instigator of climate change over these periods; i.e., CO_2 in lieu of solar activity (see also Chapter 3, this volume).

Using the regional curve standardization technique applied to ring-width measurements from living trees and relict wood, Büntgen *et al.* (2005) developed a 1,052-year summer (June–August) temperature proxy from high-elevation Alpine environments in Switzerland and the western Austrian Alps (between 46°28' to 47°00'N and 7°49' to 11°30'E). This temperature history revealed warm conditions from the beginning of the record in AD 951 to about AD 1350, which the five researchers associated with the Medieval Warm Period. Thereafter, temperatures declined and an extended cold period (the Little Ice Age) ensued, which persisted until approximately 1850, with one brief exception for a few short decades in the mid- to late-1500s, when there was an unusually warm period, the temperatures of which were exceeded only at the beginning and end of the 1,052-year record; i.e., during the Medieval and Current Warm Periods.

Holzhauser *et al.* (2005) presented high-resolution records of variations in glacier size in the Swiss Alps together with lake-level fluctuations in the Jura mountains, the northern French Pre-Alps, and the Swiss Plateau in developing a 3,500-year climate history of west-central Europe, beginning with an in-depth analysis of the Great Aletsch glacier, the largest of all the glaciers in the European Alps.

Near the beginning of the time period studied, the three researchers report, "during the late Bronze Age Optimum from 1350 to 1250 BC, the Great Aletsch glacier was approximately 1000 m shorter than it is today," noting "the period from 1450 to 1250 BC has been recognized as a warm-dry phase in other Alpine and Northern Hemisphere proxies (Tinner *et al*., 2003)." After an intervening unnamed cold-wet phase when the glacier grew in both mass and length, "during the Iron/Roman Age Optimum between c. 200 BC and AD 50," perhaps better known as the Roman Warm Period, the glacier again retreated and "reached today's extent or was even somewhat shorter than today." Next came the Dark Ages Cold Period, which they say was followed by "the Medieval Warm Period, from around AD 800 to the onset of the Little Ice Age around AD 1300." The latter cold-wet phase was "characterized by three successive [glacier length] peaks: a first maximum after 1369 (in the late 1370s), a second between 1670 and 1680, and a third at 1859/60," after which the glacier began its latest and still-ongoing recession in 1865. In addition, they state, documents from the fifteenth century AD indicate at some time during that hundred-year interval "the glacier was of a size similar to that of the 1930s," when many parts of the world were as warm as, or even warmer than, they are today, in harmony with a growing body of evidence suggesting a "Little" Medieval Warm Period occurred during the fifteenth century within the broader expanse of the Little Ice Age.

Data pertaining to the Gorner glacier (the second largest of the Swiss Alps) and the Lower Grindelwald glacier of the Bernese Alps tell much the same story, as Holzhauser *et al*. report these glaciers and the Great Aletsch glacier "experienced nearly synchronous advances" throughout the study period.

The Swiss and French scientists report "glacier maximums coincided with radiocarbon peaks, i.e., periods of weaker solar activity," which in their estimation "suggests a possible solar origin of the climate oscillations punctuating the last 3500 years in west-central Europe, in agreement with previous studies (Denton and Karlen, 1973; Magny, 1993; van Geel *et al*., 1996; Bond *et al*., 2001)." They conclude, "a comparison between the fluctuations of the Great Aletsch glacier and the variations in the atmospheric residual ^{14}C records supports the hypothesis that variations in solar activity were a major forcing factor of climate oscillations in west-central Europe during the late Holocene."

The current warmth of the region Holzhauser *et al*. studied has not yet resulted in a shrinkage of the Great Aletsch glacier equivalent to what it experienced during the Bronze Age Optimum of a little over three thousand years ago, nor what it experienced during the Roman Warm Period of two thousand years ago, suggesting there is nothing unusual or "unprecedented" about the region's current warmth. Our modern warmth is occurring at just about the time one would expect it to occur, in light of the rather consistent time intervals that separated prior warm nodes of the millennial-scale climate oscillation that produced them. This suggests Earth's current warmth, like that of prior Holocene warm periods, is likely solar-induced.

Chapron *et al*. (2005) note "millennial-scale Holocene climate fluctuations have been documented by lake level fluctuations, archaeological and palynological records for many small lakes in the Jura Mountains and several larger peri-alpine lakes." They documented the Holocene evolution of Rhone River clastic sediment supply in Lake Le Bourget via sub-bottom seismic profiling and multidisciplinary analysis of well-dated sediment cores. This revealed, as they describe it, "up to five 'Little Ice Age-like' Holocene cold periods developing enhanced Rhone River flooding activity in Lake Le Bourget documented at *c*. 7200, 5200, 2800, 1600 and 200 cal. yr BP," and "these abrupt climate changes were associated in the NW Alps with Mont Blanc glacier advances, enhanced glaciofluvial regimes and high lake levels." They also note "correlations with European lake level fluctuations and winter precipitation regimes inferred from glacier fluctuations in western Norway suggest that these five Holocene cooling events at 45°N were associated with enhanced westerlies, possibly resulting from a persistent negative mode of the North Atlantic Oscillation."

Situated between these Little Ice Age-like periods would have been Current Warm Period-like conditions. The most recent of these prior warm regimes (the Medieval Warm Period) would have been centered at about AD 1100, while the prior one (the Roman Warm Period) would have been centered in the vicinity of 200 BC, which matches well with what is known about these warm regimes from many other studies.

Robert *et al*. (2006) analyzed assemblages of minerals and microfossils from a sediment core taken from the Berre coastal lagoon in southeast France (~ 43.44°N, 5.10°E) to reconstruct environmental changes in that region over the past 1,500 years. Their analyses revealed three distinct climatic intervals: a cold period that extended from about AD 400 to 900, a warm interval between about AD 980 and 1370, and a cold interval that peaked during the sixteenth and seventeenth centuries. These climatic intervals correspond, respectively, to the Dark Ages Cold Period, Medieval Warm Period (MWP), and Little Ice Age.

The team of eight researchers also found evidence of a higher kaolinite content in the sediment core during the MWP, which suggests, they write, "increased chemical weathering in relation to higher temperatures and/or precipitation." In addition, they discovered the concentration of microfossils of the thermophilic taxon *Spiniferites bentorii* also peaked at this time, and this finding provides additional evidence the temperatures of that period were likely higher than those of the recent past.

Joerin *et al*. (2006) write, "the exceptional trend of warming during the twentieth century in relation to the last 1000 years highlights the importance of assessing natural variability of climate change." The three Swiss researchers examined glacier recessions in the Swiss Alps over the past ten thousand years based on radiocarbon-derived ages of materials found in proglacial fluvial sediments of subglacial origin, focusing on subfossil remains of wood and peat. Combining their results with earlier data of a similar nature, they constructed a master chronology of Swiss glacier fluctuations over the Holocene.

Joerin *et al*. report discovering "alpine glacier recessions occurred at least 12 times during the Holocene," once again demonstrating the reality of the millennial-scale oscillation of climate that has reverberated throughout glacial and interglacial periods alike as far back in time as scientists have searched for the phenomenon. They also determined glacier recessions have been decreasing in frequency since approximately 7,000 years ago, and especially since 3,200 years ago, "culminating in the maximum glacier extent of the 'Little Ice Age.'" Consequently, the warming of the twentieth century cannot be considered strange, since it represents a climatic rebound from the coldest period of the current interglacial, which was the coldest of the last five interglacials, according to Petit *et al*. (1999).

The last of the major glacier recessions in the Swiss Alps occurred between about 1,400 and 1,200 years ago according to Joerin *et al*.'s data, but it took place between 1,200 and 800 years ago, according to the data of Holzhauser *et al*. (2005) for the Great Aletsch Glacier. Joerin *et al*. say the two records need not be considered inconsistent with each other given the uncertainty of the radiocarbon dates. Their presentation of the Great Aletsch Glacier data also indicates the glacier's length at about AD 1000, when there was fully 100 ppm less CO_2 in the air than there is today, was slightly less than its length in 2002, suggesting the peak temperature of the Medieval Warm Period likely was slightly higher than the peak temperature of the twentieth century.

Buntgen *et al*. (2006) developed an annually resolved mean summer (June–September) temperature record for the European Alps, covering the period AD 755–2004 and based on 180 recent and historic larch (*Larix decidua* Mill.) maximum latewood density series, created via the regional curve standardization method that preserves interannual to multi-centennial temperature-related variations. They found in this history the high temperatures of the late tenth, early thirteenth, and twentieth centuries and the prolonged cooling from ~1350 to 1700, or as they describe it, "warmth during medieval and recent times, and cold in between." They report the coldest decade of the record was the 1810s, and even though the record extended through 2004, the warmest decade of the record was the 1940s. In addition, they observe, "warm summers seemed to coincide with periods of high solar activity, and cold summers vice versa." They report comparing their temperature record with other regional- and large-scale reconstructions "reveals similar decadal to longer-term variability," causing them to conclude, "the twentieth-century contribution of anthropogenic greenhouse gases and aerosol remains insecure."

Extending the work of Mangini *et al*. (2005), who had developed a 2,000-year temperature history of the central European Alps based on an analysis of $\delta^{18}O$ data obtained from stalagmite SPA 12 of Austria's Spannagel Cave, Vollweiler *et al*. (2006) used similarly measured $\delta^{18}O$ data obtained from two adjacent stalagmites (SPA 128 and SPA 70) within the same cave to create a master $\delta^{18}O$ history covering the last 9,000 years, which Mangini *et al*. (2007) compared with the Hematite-Stained-Grain (HSG) history of ice-rafted debris in North Atlantic Ocean sediments developed by Bond *et al*. (2001), who had reported "over the last 12,000 years virtually every centennial time-scale increase in drift ice documented in our North Atlantic records was tied to a solar minimum."

Mangini *et al*. found a tight correspondence between the peaks and valleys of their $\delta^{18}O$ curve and the HSG curve of Bond *et al*., concluding "the excellent match between the curves obtained from these two independent data sets gives evidence the $\delta^{18}O$ signal recorded in Spannagel cave reflects the intensity of the warm North Atlantic drift, disproving the assumption that the Spannagel isotope record is merely a local phenomenon," and, therefore, their $\delta^{18}O$ curve "can reasonably be assumed to reflect non-local conditions," implying it has wide regional applicability.

Mangini *et al*. next focus on why their $\delta^{18}O$ curve "displays larger variations for the last 2000 years than the multi-proxy record in Europe, which is mainly derived from tree-ring data" and "from low resolution archives (Mann *et al*., 1998, 1999; Mann and Jones, 2003)." The most likely answer, they write, "is that tree-rings … record the climate conditions during spring and summer," whereas both the HSG and $\delta^{18}O$ curves "mirror winter-like conditions, which are only poorly recorded in tree-rings."

Whereas the Mann *et al*. and Mann and Jones datasets do not reflect the existence of the Medieval Warm Period and Little Ice Age, the Spannagel Cave data do. Applying the calibration curve derived for SPA 12 by Mangini *et al*. (2005) to the new $\delta^{18}O$ curve, it can readily be determined the peak temperature of the Medieval Warm Period was approximately 1.5°C higher than the peak temperature of the Current Warm Period. In addition, the new dataset of Mangini *et al*. (2007) confirms the inference of Bond *et al*.'s finding that over the last 12,000 years virtually every centennial-scale cooling of the North Atlantic region "was tied to a solar minimum," demonstrating the datasets of Mann *et al*. and Mann and Jones fail to capture the full range of temperature variability over the past two millennia. The new dataset clearly depicts the existence of both the Little Ice Age and Medieval Warm Period, the latter of which is seen to have been substantially warmer over periods of centuries than the warmest parts of the twentieth century, almost certainly as a result of enhanced solar activity, and even though the air's CO_2 concentration during the Medieval Warm Period was at least 100 ppm less than it is today.

Schmidt *et al*. (2007) developed a 4,000-year climatic reconstruction by combining spring and autumn temperature anomaly reconstructions based on siliceous algae and pollen tracers found in a sediment core extracted from an Alpine lake (Oberer Landschitzsee; 47°14'52" N, 13°51'40" E) located at the southern slopes of the Austrian Central Alps just slightly above the present tree-line. They compared that reconstructed history with a similar time-scale reconstruction from another lake in the drainage area, local historical records, and other climate proxies on Alpine and Northern Hemispheric scales. They found "spring-temperature anomalies during Roman and Medieval times equaled or slightly exceeded the modern values and paralleled tree-line and glacier fluctuations." They identified "warm phases similar to present between ca. 850–1000 AD and 1200–1300 AD," which they say were "followed by climate deterioration at ca 1300 AD, which culminated during the Little Ice Age."

Schmidt *et al*. (2008) recreated the late-Holocene climate and land-use history for the region around an Austrian alpine lake, Oberer Landschitzsee (47°14'52" N, 13°51'40" E), by analyzing sediment grain size and the concentrations of major and trace elements and minerals in a 4,000-year sediment core recovered from the lake, together with autumn and spring temperature anomalies and ice cover estimated from selected pollen markers and a diatom and chrysophyte cyst thermistor-based regional calibration dataset. Their analysis identified the Roman Warm Period (300 BC to AD 400) and Medieval Warm Period (AD 1000 to AD 1600) and demonstrated "spring temperature anomalies during Roman and Medieval times equaled or slightly exceeded the modern values." They detected two other warm periods—1800 to 1300 BC and 1000 to 500 BC—as well as cooler periods between them, including the Little Ice Age that occurred between the Medieval Warm Period and the Current Warm Period. In addition, they report, "four waves of alpine land use were coupled mainly with warm periods." They found the two warm periods that preceded the Current Warm Period were at least as warm as today.

Millet *et al*. (2009) write, "among biological proxies from lake sediments, chironomid [non-biting midge] assemblages are viewed as one of the most promising climatic indicators," and "the accuracy of chironomid assemblages for the reconstruction of Lateglacial temperatures is now broadly demonstrated." They developed a new chironomid-based temperature record from Lake Anterne (northern French Alps) covering the past two millennia, compared that reconstruction with other late-Holocene temperature records from Central Europe, and addressed the question of whether previously described centennial-scale climate events such as the Medieval Warm Period or Little Ice Age can be detected in this new summer temperature record, noting "at a hemispheric or global scale the existence of the LIA and MWP have been questioned."

The six scientists report they found evidence "of a cold phase at Lake Anterne between AD 400 and 680, a warm episode between AD 680 and 1350, and another cold phase between AD 1350 and 1900," stating these events were "correlated to the so-called 'Dark Age Cold Period' (DACP), the 'Medieval Warm Period' and the 'Little Ice Age.'" They note "many other climate reconstructions across western Europe confirm the existence of several significant climatic changes during the last 1800 years in Central Europe and more specifically the DACP, the MWP and the LIA." They also report the reconstructed temperatures of the twentieth century failed to show a return to MWP levels of warmth, but they attribute that to a breakdown of the chironomid-temperature relationship over the final century of their 1,800-year history.

Corona *et al*. (2010) analyzed tree-ring width data obtained from 548 trees (living and dead) at 34 sites distributed across the French Alps (44°–45°30'N, 6°30'–7°45'E), which they calibrated against monthly homogenized records of temperature obtained from a network of 134 meteorological stations extending back to AD 1760, to develop a summer (June, July, August) temperature history for the period AD 751–2008 using the Regional Curve Standardization technique, which they say "has been shown to be the most appropriate age-related detrending method for preserving multi-centennial climate variability." This work revealed, they write, "most of the 20th century is comparable with the Medieval Warm Period," but "during the last decade of the 20th century, the amplitude and abruptness of the summer temperature increase exceed the warming reconstructed for the Medieval Warm Period." From their graph of the data, that exceedance appears to be about 0.4°C.

Gasiorowski and Sienkiewicz (2010) inferred the thermal conditions of Smreczynski Staw Lake (49°12'N, 19°51'E) in the Tatra Mountains of southern Poland via analyses of the distributions of various cladocera, chironomid, and diatom species they identified and quantified in a sediment core extracted from the center of the lake in the spring of 2003, which contained sediments that had accumulated there over the prior 1,500 years. This work revealed the presence of "a diverse ecosystem at the beginning of [the] record, ca. AD 360–570," which has typically been assigned to the Dark Ages Cold Period. They found from AD 570 to 1220 "environmental conditions were better," and various cold-water taxa were "totally absent." The younger section of this zone—approximately its upper third (AD 850–1150), which contained the highest concentration of warm-water *Chironomus* species—"can be correlated with the Medieval Warm Period," they write. Next came the Little Ice Age, which was the focal point of their study, extending to the start of the twentieth century, after which relative warmth once again returned, persisting to the present. Based on the *Chironomus* concentrations of the Current Warm Period, their data suggest the peak warmth of the CWP and the earlier MWP were about the same.

Sorrel *et al*. (2010) documented "the depositional history of the inner bay coeval to the mid- to late-Holocene transgression in south Brittany," based on "an approach combining AMS ^{14}C [radiocarbon] dating, sedimentological and rock magnetic analyses on sediment cores complemented with seismic data collected in the macrotidal Bay of Vilaine [47°20'–47°35'N, 2°50'–2°30'W]." According to the authors, "the late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives," where they found "an increase in the contribution of riverine inputs occurred during the MWP" at "times of strong fluvial influences in the estuary during ca. 880–1050 AD." They note, "preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal," in accordance with the findings of Proctor *et al*. (2000) and Meeker and Mayewski (2002). They also note the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon *et al*. (2004) and Billeaud *et al*. (2005). They write, "all sedimentary records from the French and Spanish Atlantic coasts" suggest "the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development." In addition, "milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths," they write.

The eight researchers state the upper successions of the sediment cores "mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals," noting "this shift most probably documents the transition from the MWP to the Little Ice Age," which led to the "increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and Rendell, 2009)" associated with "the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard *et al*., 2007; Clemmensen *et al*., 2007, 2009; Matthews and Briffa, 2005), France (Meurisse *et al*., 2005), Netherlands (Jelgersma *et al*., 1995) and Scotland (Dawson *et al*., 2004)." In what they call an even "wider perspective," they note the Medieval Warm Period "is recognized as the warmest period of the last two millennia (Mayewski *et al*., 2004; Moberg *et al*., 2005)."

The French scientists ultimately conclude "the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD," suggesting "climatic conditions were probably mild enough to prevent coastal erosion in northwestern France" during this period.

Larocque-Tobler *et al*. (2010) argue "new records to increase the geographic coverage of paleoclimatic information are needed" to better describe the amplitude of temperature change during the last millennium, and "only by obtaining numerous high-resolution temperature records will it be possible to determine if the 20th century climate change exceeded the natural pre-industrial variability of European climate." They obtained a temperature record spanning the last millennium via an analysis of fossil chironomids (non-biting midges), which they identified and quantified in four sediment cores extracted from the bed of Lake Silvaplana (46°26'56"N, 9°47'33"E) in the Upper Engadine (a high-elevation valley in the eastern Swiss Alps).

This work revealed, "at the beginning of the record, corresponding to the last part of the 'Medieval Climate Anomaly' (here the period between *ca.* AD 1032 and 1262), the chironomid-inferred mean July air temperatures were 1°C warmer than the climate reference period (1961–1990)." Their graphs of 20- and 50-year running means (see Figure 4.2.4.6.1.3) show the peak mean warmth of the Medieval Warm Period exceeded that of the Current Warm Period by about 0.5°C in the case of 20-year averages and 1.2°C in the case of 50-year averages. Thus the five researchers conclude, "based on the chironomid-inferred temperatures, there is no evidence mean-July air temperature exceeded the natural variability recorded during the Medieval Climate Anomaly in the 20th century at Lake Silvaplana," noting similar results "were also obtained in northern Sweden (Grudd, 2008), in Western Europe (Guiot *et al*., 2005), in a composite of Northern Hemisphere tree-ring reconstructions (Esper *et al*., 2002) and a composite of tree rings and other archives (Moberg *et al*., 2005)."

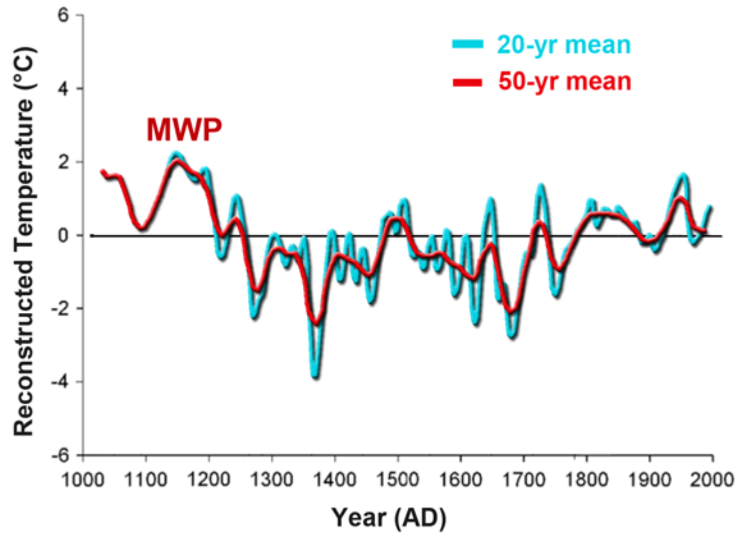

Figure 4.2.4.6.1.3. Temperature reconstruction obtained from sediment cores extracted from the bed of Lake Silvaplana in the eastern Swiss Alps. Adapted from Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M., and Kamenik, C. 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. *Quaternary Science Reviews* **29**: 1940–1949.

Scapozza *et al*. (2010) used radiocarbon dating of the fossil wood remains of eight larch (*Larix decidua*) stem fragments found one meter beneath the surface of the ground at the base of the front of the Piancabella rock glacier (46°27'02" N, 9°00'07" E) in the Southern Swiss Alps in September 2005, determining the wood was formed somewhere between AD 1040 and 1280 with a statistical probability of 95.4 percent. Based on this information and "geomorphological, climatological and geo-physical observations," they inferred "the treeline in the Medieval Warm Period was about 200 meters higher than in the middle of the 20th century, which corresponds to a mean summer temperature as much as 1.2°C warmer than in AD 1950." Adjusting for warming between 1950 and the present, it can be estimated the MWP was about 0.5°C warmer than the peak warmth of the CWP.

Magny *et al*. (2011) write, "present-day global warming has provoked an increasing interest in the reconstruction of climate changes over the last millennium (Guiot *et al*., 2005; Jones *et al*., 2009)," which time interval is "characterized by a succession of distinct climatic phases, i.e. a Medieval Warm Period (MWP) followed by a long cooler Little Ice Age (LIA) and finally by a post-industrial rapid increase in temperature," generally referred to as the initial phase of the Current Warm Period (CWP). In a study designed to compare the temperatures of these periods, the six scientists, working at Lake Joux (46°36'N, 6°15'E) at an altitude of 1,006 meters above sea level (a.s.l.) in the Swiss Jura Mountains, employed a multi-proxy approach with pollen and lake-level data to develop a 1,000-year history of the mean temperature of the warmest month of the year (MTWA, which was July at Lake Joux), based on the Modern Analogue Technique. They describe this procedure as "a commonly used and accepted method for the reconstruction of Lateglacial and Holocene climate oscillations from continental and marine sequences," citing Guiot *et al*. (1993), Cheddadi *et al*., (1997), Davis *et al*. (2003), Peyron *et al*. (2005), Kotthoff *et al*. (2008), and Pross *et al*. (2009).

Magny *et al*. report their data "give evidence of the successive climate periods generally recognized within the last 1000 years," which they describe as "a MWP between ca. AD 1100 and 1320, (2) a LIA which, in the Joux Valley, initiated as early as ca. AD 1350 and ended at ca. AD 1870, and (3) a last warmer and drier period," generally referred to as the beginning of the Current Warm Period (CWP).

"Considering the question of present-day global warming on a regional scale," Magny *et al*. write, "the increase in MTWA by ca. 1.6°C observed at Laoura (1100 m a.s.l., near the Joux basin) for the period 1991–2008, when compared to the reference period 1961–1990, still appears to be in the range of the positive temperature anomaly reconstructed at Lake Joux ca. AD 1300 during the late MWP." They note "meteorological data observed at La Brevine (1043 m a.s.l., also near the Joux basin) suggest a similar pattern with an increase in MTWA by 1°C over the period 1991–2008" relative to 1961–1990. Both of these late-twentieth/early twenty-first century temperature increases fall significantly short of that reached during the MWP, when the temperature at Joux Lake exceeded that of the 1961–1990 reference period by fully 2.0°C. The peak warmth of the MWP at Lake Joux appears to have exceeded that of the CWP at that location by 0.4–1.0°C, in harmony with similar findings obtained at other locations around the world.

Swieta-Musznicka *et al*. (2011) analyzed pollen and macrofossils taken from trench walls exposed during archaeological excavations in Gdansk (54°22'N, 18°40'E), northern Poland, as well as with similar materials contained within cores retrieved from sediments lying beneath the trenches, and discovered evidence for a population expansion of *Salvinia natans* (an aquatic fern) in the seventh or eighth century AD, which was similar to a climate-driven population expansion during the last decade. They report, "the co-occurrence of *S. natans* with other aquatic plant species was similar in both the medieval and present-day vegetation," and "the high density of *S. natans* in the medieval population caused impoverishment of the local ecosystems in a way that has been observed in recent water bodies affected by invasive pleustophytes (free-floating plants)." Thus they conclude "the *S. natans* 'blooms' in the Early Middle Ages may be regarded as an extraordinary occurrence that has an analogue in the climate-driven population of this species during the last decade."

The four researchers describe the early period of *S. natans* population expansion as being due to "climate warming similar to the present time." Elsewhere they report, "in the early medieval period, the population density of *S. natans* was similar to or higher than that observed today in shallow waters invaded by this species in the Gdansk region." Their work suggests the medieval warmth of this part of the world was at least equal to, and perhaps warming than, the CWP.

Moschen *et al*. (2011) presented "a high resolution reconstruction of local growing season temperature anomalies at Durres Maar, Germany [50°52'N, 6°53'E], spanning the last two millennia," which was "derived from a stable carbon isotope time series of cellulose chemically extracted from *Sphagnum* leaves (δ^{13}Ccellulose) separated from a kettle-hole peat deposit of several meters thickness," where the temperature reconstruction was based on the temperature dependency of *Sphagnum* δ^{13}Ccellulose observed in calibration studies (Figure 4.2.4.6.1.4). The five researchers identified a cold phase with below-average temperature, lasting from the fourth to the seventh century AD, "in accordance with the so-called European Migration Period," which has come to be known as the Dark Ages Cold Period. Thereafter, they state, "during High Medieval Times above-average temperatures are obvious." The peak warmth of this Medieval Warm Period, which looks from the graph of their data to run from about AD 830 to AD 1150, was approximately 2.8°C greater than the peak warmth of the Current Warm Period in terms of individual anomaly points, and it was approximately 2.7°C greater in terms of 60-year running means. Between these two warm periods, the Little Ice Age could be seen to hold sway.

Expanding upon the work of some of their group two years earlier (Larocque-Tobler *et al*., 2010), Larocque-Tobler *et al*. (2012) note "the climate of the last millennium is still controversial because too few high-resolution paleo-climate recon-structions exist to answer two key research questions"; namely, "Were the 'Medieval Climate Anomaly' (MCA) and the 'Little Ice Age' (LIA) of similar spatial extent and timing in Europe and in the Northern Hemisphere?" and "Does the amplitude of climate change of the last century exceed the natural variability?"

The second Larocque-Tobler team analyzed a lake sediment core extracted from the deepest point of Seebergsee (46°37'N, 7°28'E) in the northern Swiss Alps in AD 2005, employing chironomid head capsules preserved in the sediments to reconstruct mean July air temperatures for the past 1,000 years.

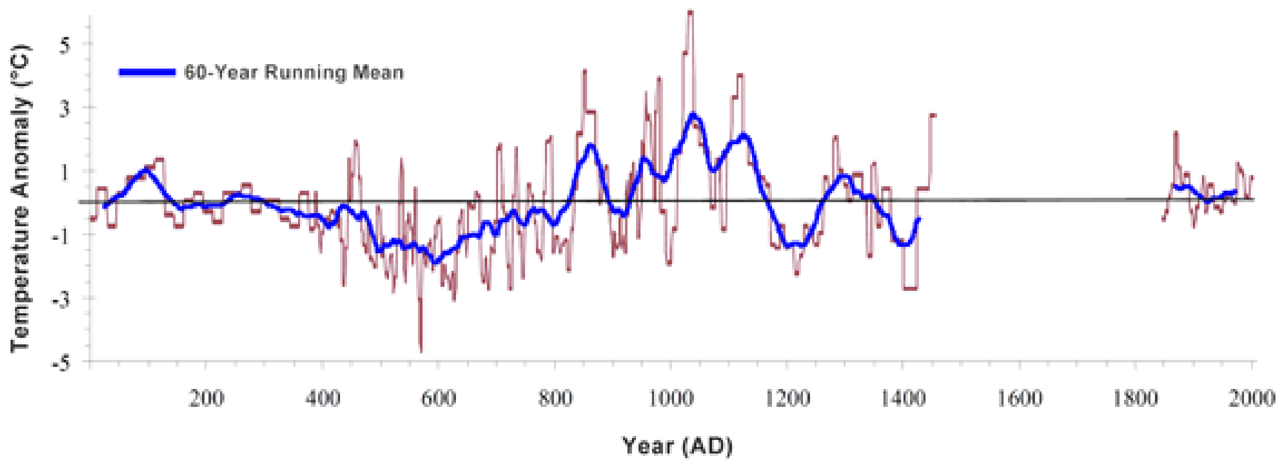

Figure 4.2.4.6.1.4. Temperature reconstruction from Durres Marr, Germany. Adapted from Moschen, R., Kuhl, N., Peters, S., Vos, H., and Lucke, A. 2011. Temperature variability at Durres Maar, Germany during the Migration Period and at High Medieval Times, inferred from stable carbon isotopes of *Sphagnum* cellulose. *Climate of the Past* **7**: 1011–1026.

They compared their results to those of Larocque-Tobler *et al*. (2010) for another Swiss lake (Silvaplana in the eastern Alps) and to regional and European records of early instrumental data (Luterbacher *et al*., 2004; Auer *et al*., 2007; Bohm *et al*., 2010), as well as a composite of paleoclimate reconstructions from the Greater Alpine Region and to millennial scale climate reconstructions of the entire Northern Hemisphere (Mangini *et al*., 2005; Moberg *et al*., 2005; Osborn and Briffa, 2006).

The six scientists' work revealed the peak warmth of the MCA just prior to AD 1200 was approximately 0.9°C greater than the peak warmth near the end of their record, as can be determined from the graph of their data, reproduced here as Figure 4.2.4.6.1.5. The IPCC-endorsed "hockey stick" temperature record of Mann *et al*. (1999), which gives little indication of the existence of the MCA and shows recent temperatures towering over those of that earlier time period, continues to be repudiated by real-world data. Larocque-Tobler *et al*. note their newest temperature history is "mirrored by the chironomid reconstruction from Silvaplana and the Greater Alpine Region composite of reconstructions" and "several other reconstructions from the Northern Hemisphere also show [recent] warm inferred temperatures that were not as warm as the MCA."

Niemann *et al*. (2012) point out, as so many others have, "the assessment of climate variations in Earth's history is of paramount importance for our comprehension of recent and future climate variability." Noting "geological archives containing climate-sensitive proxy indicators are used to recon-struct paleoclimate," Niemann *et al*. employed what they describe as "a novel proxy for continental mean annual air temperature (MAAT) and soil pH" "based on the temperature (T) and pH-dependent distribution of specific bacterial membrane lipids (branched glycerol dialkyl glycerol tetraethers—GDGTs) in soil organic matter." This technique derives from the fact that "microorganisms can modify the composition of their cellular membrane lipids to adapt membrane functionality to specific environmental parameters such as T and pH," as described by Hazel and Williams (1990) and Weijers *et al*. (2007), the latter of whom devised "transfer functions that relate the degree of the GDGT methylation (expressed in the Methylation index—MBT) and cyclisation (expressed in the cyclisation ratio—CBT) to mean annual air temperature."

Niemann *et al*. used sediment cores collected in September 2009 and May 2010 from a small alpine lake (Cadagno) in the Piora Valley of south-central Switzerland, as well as soil samples taken from the surrounding catchment area. The nine Dutch and Swiss researchers report "major climate anomalies recorded by the MBT/CBT-paleothermometer" were "the Little Ice Age (~14th to 19th century) and the Medieval Warm Period (MWP, ~9th to 14th century)," which they say experienced "temperatures similar to the present-day values." They also report, "in addition to the MWP," their "lacustrine paleo T

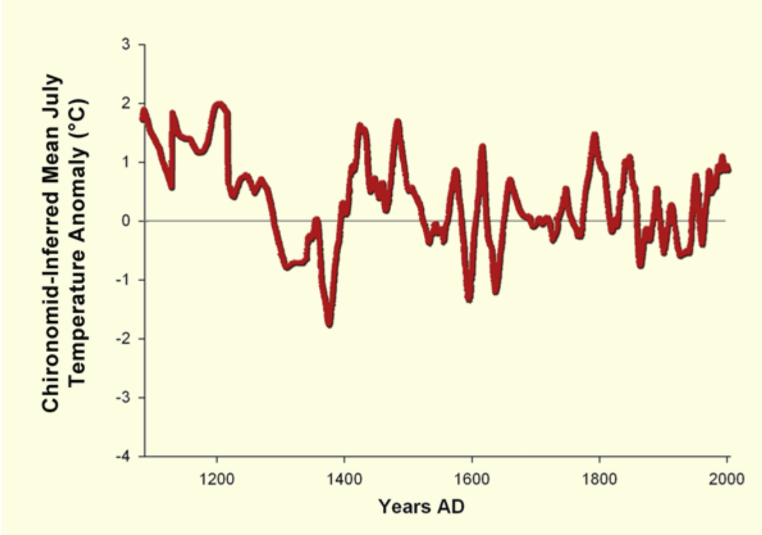

Figure 4.2.4.6.1.5. Reconstruct chironomid-inferred mean July air temperatures for the past 1,000 years, as obtained from a lake sediment core extracted from the deepest point of Seebergsee (46°37'N, 7°28'E) in the northern Swiss Alps. Adapted from Larocque-Tobler, I., Stewart, M.M., Quinlan, R., Traschel, M., Kamenik, C., and Grosjean, M. 2012. A last millennium temperature reconstruction using chironomids preserved in sediments of anoxic Seebergsee (Switzerland): consensus at local, regional and Central European scales. *Quaternary Science Reviews* **41**: 49–56.

record indicates Holocene warm phases at about 3, 5, 7 and 11 kyr before present, which agrees in timing with other records from both the Alps and the sub-polar North-East Atlantic Ocean."

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4.2.4.6.2 Northern

Studying "four well-preserved continuous sediment sequences from the southern flank of the Skagerrak [58.2-58.6°N, 7.6-8.2°E]," which he described as "a current-controlled sedimentary basin between the North and Baltic Seas," Hass (1996) carried out "granulometric and stable oxygen isotope analyses ... in order to reconstruct climate fluctuations and to evaluate climate impact during the upper Holocene." He concludes the "Modern Climate Optimum was reached between 1940 and 1950, when temperatures exceeded the present day mean by 0.5°C." Prior to that was the Little Ice Age, which he placed at about AD 1350–1900, and before that the Medieval Warm Period (AD 800/1000–1350), the climate of which "was characterized by warm summers, mild winters and little storm activity." Preceding this interval was what has been called the Dark Ages Cold Period, which Hass did not name but placed between AD 400 and 700, and preceding that cold spell was the Roman Warm Period, from approximately 400 BC to AD 400. Preceding these climatic epochs was another pair of cold and warm periods.

Hass's work adds to the evidence supporting the reality of a repetitive worldwide cycling of climate between Medieval Warm Period- and Little Ice Age-like conditions. In addition, he notes, "at the onset of the Modern Climate Optimum ... conditions change again to a level comparable to the Medieval Warm Period.

Kullman (1998) reviewed "past positional, structural and compositional shifts of tree-limits and upper boreal forests, mainly in the southern Scandes Mountains of Sweden," based on studies of the elevational location of well-dated subfossil wood remains and the known change in air temperature with change in elevation. Among other things, he discovered "some exceptionally warm and stable centuries, with high tree-limits and dense montane forests, occurred during the Medieval period." He also found "an episode of warmer climate during the first half of the [twentieth] century," but he notes tree limits and high-elevation forests at that time "were far from restored to their medieval levels," which by AD 900–1100 "were situated 80–100 meters higher" than they were about a century ago; i.e., ~1900. He also reports "during the past few decades"—that is, during the latter part of the twentieth century—there was widespread "rapid cold-induced dieback."

The Swedish scientist states, "the slight cooling and associated tree-limit and forest responses since the climate optimum in the late 1930s fit a more general pattern, common to the entire North Atlantic seaboard and adjacent continental areas." He reports "there appear to have been no detectable regional or global tree-limit progression trends over the past 2–3 decades matching the GCM climate projections based on increasing CO_2 levels." He thus concludes "since tree-limits in Scandinavia or elsewhere in the world have not reestablished at their Medieval levels, it is still possible that today's climate, despite centennial net warming, is within its natural limits."

Andren *et al*. (2000) conducted an extensive analysis of changes in siliceous microfossil assemblages and chemical characteristics of various materials found in a well-dated sediment core obtained from the Bornholm Basin in the southwestern Baltic Sea. The data revealed the existence of a period of high primary production at approximately AD 1050, and contemporaneous diatoms were warm water species such as *Pseudosolenia calcar-avis*, which they indicate is "a common tropical and subtropical marine planktonic species" that "cannot be found in the present Baltic Sea." They also note what they call the Recent Baltic Sea Stage, which began about AD 1200, starts "at a point where there is a major decrease in warm water taxa in the diatom assemblage and an increase in cold water taxa, indicating a shift towards a colder climate," which they associate with the Little Ice Age. Andren *et al*.'s data further indicate there was a period of time in the early part of the past millennium when the climate in the area of the southwestern Baltic Sea was warmer than it is today, as the sediment record of that time and vicinity contained several warm water species of diatoms, some of which can no longer be found there. This period of higher temperatures falls within "a period of early Medieval warmth dated to AD 1000–1100," which they note "corresponds to the time when the Vikings succeeded in colonizing Iceland and Greenland."

Hiller *et al*. (2001) analyzed subfossil wood samples from the Khibiny mountains in the Kola Peninsula (67–68°N, 33–34°E) to reconstruct climate change there over the past 1,500 years. They determined between AD 1000 and 1300 the tree-line was located at least 100–140 m above its current elevation, an advance they describe as suggesting mean summer temperatures during this "Medieval climatic optimum" were "at least 0.8°C higher than today." They describe this time period as hosting "the most pronounced warm climate phase on the Kola Peninsula during the last 1500 years,"

Nesje *et al*. (2001) analyzed a 572-cm-long sediment core retrieved from Norway's Lake Atnsjoen to determine the frequency and magnitude of prehistoric floods in the southern part of that country. These efforts revealed several pronounced floods occurred throughout the 4,500-year period. The more recent portion of the record showed a time "of little flood activity around the Medieval period (AD 1000-1400)," correlated with reduced regional glacier activity, and a subsequent period of "the most extensive flood activity in the Atnsjoen catchment," which resulted from the "post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age.'"

Mikalsen *et al*. (2001) conducted detailed analyses of benthic foraminifera, stable isotopes, and other sedimentary material obtained from a core extracted from a fjord in western Norway, from which they derived a relative temperature history of the region that spanned the last 5,500 years. This work revealed four cold periods characterized by 1.5–2°C reductions in bottom-water temperature—2150 to 1800 BC, 850 to 600 BC, 150 BC to AD 150, AD 500 to 600—and "a cooling that may correspond to the 'Little Ice Age' (AD 1625)." The three researchers also note "there is a good correlation between the cold periods and cold events recorded in other studies." They also identified a warm period from AD 1330 to 1600 that "had the highest bottom-water temperatures in Sulafjorden during the last 5000 years."

Brooks and Birks (2001) were deeply involved in refining protocols for using the larval-stage head capsules of midges to reconstruct temperature histories of various locations, and in this particular paper they report their progress and illustrate the application of their techniques to certain locations in Scotland and Norway. Of particular interest to the

CO_2-climate debate are their findings for Lochan Uaine, in the Cairngorms region of the Scottish Highlands. This lake, they write, "is remote from human habitation and therefore any response of proxy indicators to climatic change [is] unlikely to be masked by the effects of anthropogenic environmental change in its catchment." Reconstructed temperatures for this region peaked at about 11°C, during what they refer to as the "Little Climatic Optimum"—more typically called the Medieval Warm Period—"before cooling by about 1.5°C which may coincide with the 'Little Ice Age.'" These results, say the two scientists, "are in good agreement with a chironomid stratigraphy from Finse, western Norway (Velle, 1998)," where summer temperatures were "about 0.4°C warmer than the present day" during the Medieval Warm Period. The latter observation also appears true for Brooks and Birks' study, since the upper sample of the Lochane Uaine core, collected in 1993, "reconstructs the modern temperature at about 10.5°C" which is 0.5°C less than the 11°C value they obtained from the Medieval Warm Period.

McDermott *et al*. (2001) derived a $\delta^{18}O$ record from a stalagmite discovered in Crag Cave in southwestern Ireland. They compared this record with the $\delta^{18}O$ records from the GRIP and GISP2 ice cores from Greenland. They found "centennial-scale δ ^{18}O variations that correlate with subtle $\delta^{18}O$ changes in the Greenland ice cores, indicating regionally coherent variability in the early Holocene." They also report the Crag Cave data "exhibit variations that are broadly consistent with a Medieval Warm Period at ~1000 ± 200 years ago and a two-stage Little Ice Age, as reconstructed by inverse modeling of temperature profiles in the Greenland Ice Sheet." Also evident in the Crag Cave data were the $\delta^{18}O$ signatures of the earlier Roman Warm Period and Dark Ages Cold Period. The three researchers note the coherent $\delta^{18}O$ variations in the records from both sides of the North Atlantic "indicate that many of the subtle multicentury $\delta^{18}O$ variations in the Greenland ice cores reflect regional North Atlantic margin climate signals rather than local effects." Their data confirm the reality of the Medieval Warm Period/Little Ice Age cycle and the prior and even-more-strongly-expressed Roman Warm Period/Dark Ages Cold Period cycle.

Voronina *et al*. (2001) analyzed dinoflagellate cyst assemblages in two sediment cores from the southeastern Barents Sea—one spanning a period of 8,300 years and one for 4,400 years—obtaining information about sea-surface salinity, temperature, and ice cover throughout the mid- to late-Holocene. The longer of the two cores indicated a warm interval from about 8,000 to 3,000 years before present, followed by cooling pulses coincident with lowered salinity and extended ice cover in the vicinity of 5,000, 3,500, and 2,500 years ago. The shorter of the two cores also revealed cooling pulses at tentative dates of 1,400, 300, and 100 years before present. For the bulk of the past 4,400 years, ice cover lasted only two to three months per year, as opposed to the modern mean of 4.3 months per year, and August temperatures ranged between 6 and 8°C, significantly warmer than the present mean of 4.6°C. This is evidence of considerably warmer temperatures than those of today over much of the past few thousand years—including a period of time coeval with the Medieval Warm Period—in the southeastern Barents Sea, which conditions are said by Voronina *et al*. to be reflective of conditions throughout northwestern Eurasia.

Gunnarson and Linderholm (2002) worked with living and subfossil Scots pine (*Pinus sylvestris* L.) sampled close to the present tree-line in the central Scandinavian Mountains to develop a continuous 1,091-year tree-ring width chronology running from AD 909 to 1998, which they determined to be a good proxy for summer temperatures in the region. They report their data "support evidence for a 'Medieval Warm Period,' where growth conditions were favorable in the tenth and early eleventh centuries." In addition, their data show the warmth of the Medieval Warm Period was both greater and longer-lasting than that of the Current Warm Period, which their data depict as having peaked around 1950.

The two Swedish scientists report their chronology "does not show the continuous temperature decrease from AD 1000 to 1900 followed by a distinct increase during the twentieth century" shown by the hockey stick temperature history of Mann *et al*. (1998, 1999). "On the contrary," they write, their chronology "displays a positive trend from the middle of the seventeenth century, culminating around 1950, followed by strongly decreasing growth."

Berglund (2003) identified several periods of expansion and decline of human cultures in Northwest Europe and compared them with a history of reconstructed climate "based on insolation, glacier activity, lake and sea levels, bog growth, tree line, and tree growth." He found "a positive correlation between human impact/land-use and climate change."

Specifically, in the latter part of the record, where both cultural and climate changes were best defined, there was, in his words, a great “retreat of agriculture” centered on about AD 500, which led to “reforestation in large areas of central Europe and Scandinavia.” He additionally notes “this period was one of rapid cooling indicated from tree-ring data (Eronen *et al*., 1999) as well as sea surface temperatures based on diatom stratigraphy in [the] Norwegian Sea (Jansen and Koc, 2000), which can be correlated with Bond’s event 1 in North Atlantic sediments (Bond *et al*., 1997).”

Next came what Berglund called a “boom period” that covered “several centuries from AD 700 to 1100.” This period proved to be “a favorable period for agriculture in marginal areas of Northwest Europe, leading into the so-called Medieval Warm Epoch,” when “the climate was warm and dry, with high treelines, glacier retreat, and reduced lake catchment erosion.” This period “lasted until around AD 1200, when there was a gradual change to cool/moist climate, the beginning of the Little Ice Age ... with severe consequences for the agrarian society.”

Andersson *et al*. (2003) inferred surface conditions of the eastern Norwegian Sea (Voring Plateau) from planktic stable isotopes and planktic foraminiferal assemblage concentrations in two seabed sediment cores obtained in the vicinity of 66.97°N, 7.64°W that covered the last three thousand years. The climate history derived from this study was remarkably similar to that derived by McDermott *et al*. (2001) from a high-resolution speleothem $\delta^{18}O$ record obtained from a stalagmite discovered in a cave in southwestern Ireland. At the beginning of the 3,000-year-long Voring Plateau record, for example, both regions were clearly in the end-stage of the long cold period that preceded the Roman Warm Period. Both records depicted warming from that time to the peak of the Roman Warm Period, which occurred about 2,000 years BP. Both regions then began their descent into the Dark Ages Cold Period, which lasted until the increase in temperature that produced the Medieval Warm Period, which in both records prevailed from about 800 to 550 years BP. Finally, the Little Ice Age was evident, with cold periods centered at approximately 400 and 100 years BP, again in both records.

Interestingly, neither record indicates the existence of what has come to be called the Current Warm Period. Moreover, Andersson *et al*. report, “surface ocean conditions warmer than present were common during the past 3000 years.” As time has passed, therefore, evidence for the reality of the solar-induced millennial-scale cycling of climate described by Bond *et al*. (1997, 2001) has continued to mount, while evidence for the “unprecedented” temperature claimed for the present by the IPCC continues to be sought but not found.

Tiljander *et al*. (2003) conducted high-resolution analyses—including varve thickness, relative X-ray density, pollen and diatom assessments, and organic matter loss-on-ignition (LOI)—on a 3,000-year varved sediment sequence obtained from Lake Korttajarvi in central Finland. They compared their results with those of other palaeo-environmental studies conducted in Finland. They found “an organic rich period from AD 980 to 1250” they say “is chronologically comparable with the well-known ‘Medieval Warm Period.’” During time period, they report, “the sediment structure changes” and “less mineral material accumulates on the lake bottom than at any other time in the 3000 years sequence analyzed and the sediment is quite organic rich (LOI ~20%).” They conclude, “the winter snow cover must have been negligible, if it existed at all, and spring floods must have been of considerably lower magnitude than during the instrumental period (since AD 1881),” conditions they equate with a winter temperature approximately 2°C warmer than at present.

Tiljander *et al*. cite much corroborative evidence in support of this conclusion. They note, for example, “the relative lack of mineral matter accumulation and high proportion of organic material between AD 950 and 1200 was also noticed in two varved lakes in eastern Finland (Saarinen *et al*., 2001) as well as in varves of Lake Nautajarvi in central Finland c. AD 1000–1200 (Ojala, 2001).” They also note “a study based on oak barrels, which were used to pay taxes in AD 1250–1300, indicates oak forests grew 150 km north of their present distribution in SW Finland and this latitudinal extension implies a summer temperature 1–2°C higher than today (Hulden, 2001).” And they report “a pollen reconstruction from northern Finland suggests that the July mean temperature was c. 0.8°C warmer than today during the Medieval Climate Anomaly (Seppa, 2001).” In these studies, therefore, the scientists conclude both summer and winter temperatures over much of the Medieval Warm Period throughout many parts of Finland were significantly warmer than they are at present.

Roncaglia (2004) analyzed variations in organic matter deposition from approximately 6,350 cal yr BC to AD 1430 in a sediment core extracted from the

Skalafjord, southern Eysturoy, Faroe Islands to assess climatic conditions in that part of the North Atlantic from the mid- to late-Holocene. She reports an increase in "structured brown phytoclasts, plant tissue and sporomorphs in the sediments dating to ca. AD 830–1090 indicate increased terrestrial influx and inland vegetation supporting the idea of improved climatic conditions," while also noting "the increase in the amount of structured brown phytoclasts, leaf and membranous tissue and sporomorphs indicated increased inland vegetation probably related to improved climatic conditions and/or the presence of cultivated crops on the islands." In addition, she found high "total dinoflagellate cyst concentration and increased absolute amount of loricae of tintinnid and planktonic crustacean eggs occurred at ca. AD 830–1090," concluding these observations "may suggest increased primary productivity in the waters of the fjord," citing Lewis *et al*. (1990) and Sangiorgi *et al*. (2002).

Roncaglia writes, the "amelioration of climate conditions," which promoted the enhanced productivity of both land and sea at this time, "may encompass the Medieval Warm Period in the Faroe region." She also reports an increased concentration of certain other organisms at about AD 1090–1260, which she says "suggests a cooling, which may reflect the beginning of the Little Ice Age." Thus evidence for both the Medieval Warm Period and Little Ice Age is clear in the sediments of a Faroe Island fjord, demonstrating that even at sea, these major recurring extremes of cyclical Holocene climate make their presence felt to such a degree that they significantly influence both aquatic and terrestrial primary production.

Hormes *et al*. (2004) identified and dated periods of soil formation in moraines in the Kebnekaise mountain region of Swedish Lapland in the foreground of the Nipalsglaciaren (67°58'N, 18°33'E) and compared the climatic implications of their results with those of other proxy climate records derived in other areas of northern and central Scandinavia. Two main periods of soil formation were identified (2750–2000 and 1170–740 cal yr BP), and these time spans coincide nearly perfectly with the Roman and Medieval Warm Periods delineated by McDermott *et al*. (2001) in the high-resolution $\delta^{18}O$ record they developed from a stalagmite in southwestern Ireland's Crag Cave.

Hormes *et al*. also report the periods during which the soil formation processes took place "represent periods where the Nipalsglacier did not reach the position of the moraine," and "the glacier was most likely in a position similar to today, and climate conditions were also similar to today." Comparing their findings with those of other investigators, they report the following with respect to the Medieval Warm Period:

(1) Pollen profiles derived from sediments of Lake Tibetanus in Lapland (Hammarlund *et al*., 2002) "infer increased mean July temperatures ... peaking around 1000 cal yr BP."

(2) Oxygen isotope studies in nearby Lake 850 "record changes around 1000 cal yr BP towards favorable climate conditions (Shemesh *et al*., 2001)."

(3) At Lake Laihalampi in southern Finland, "pollen-based reconstructions of mean temperatures indicate 0.5°C higher values between 1200 and 1100 cal yr BP (Heikkila and Seppa, 2003)."

(4) Radiocarbon ages of mosses in front of Arjep Ruotesjekna in the Sarek Mountains of Swedish Lapland "support the conclusion that between 1170 and 920 cal yr BP the glaciers had not reached the 1970s limit (Karlen and Denton, 1975)."

(5) Reconstructed temperatures of a pine dendrochronology from northern Fennoscandia "show temperatures between 1100 and 750 cal yr BP to have been around 0.8°C higher than today (Grudd *et al*., 2002)."

(6, 7) At Haugabreen glacier (Matthews, 1980) and Storbreen glacier (Griffey and Matthews, 1978) in southern maritime Norway, "soil formation on moraines was dated between 1060 and 790 cal yr BP."

(8) Alder trees were melted out from Engabreen glacier (Worsley and Alexander, 1976), "suggesting a smaller extension of this Norwegian glacier between 1180 and 790 cal yr BP supporting warm/dry conditions during that time in central Norway."

(9) Jostedalsbreen glacier "receded between 1000 and 900 cal yr BP (Nesje *et al*., 2001)."

With respect to their identification of the Roman Warm Period, Hormes *et al*. report prior findings of soil formation at (1) Svartisen glacier between 2,350 and 1,990 cal yr BP by Karlen (1979), (2) Austre Okstindbreen glacier between 2,350 and 1,800 cal yr BP by Griffey and Worsley (1978), and (3) Austre Okstindbreen glacier between 2,750 and 2,150 by Karlen (1979). In addition, they note:

(4) The pine tree-based temperature history of northern Fennoscandia developed by Grudd *et al*. (2002) "discloses a spike +2°C higher than today's around 2300 cal yr BP."

(5, 6, 7, 8, 9) "The lacustrine records in Lapland

and Finland are also consistent with supposition of a warmer climate than at present before 2000 cal yr BP and cooler temperatures before 2450 cal yr BP (Rosen *et al*., 2001; Seppa and Birks, 2001; Shemesh *et al*., 2001; Hammarlund *et al*., 2002; Heikkila and Seppa, 2003)."

In view of these many research findings, it is clear both the Medieval and Roman Warm Periods were very real features of Scandinavian climatic history, and they were likely even warmer than the Current Warm Period has been to date.

Blundell and Barber (2005) used plant macrofossils, testate amoebae, and degree of humification as proxies for environmental moisture conditions to develop a 2,800-year "wetness history" from a peat core extracted from Tore Hill Moss, a raised bog in the Strathspey region of Scotland. Based on the results they obtained from the three proxies they studied, they derived a relative wetness history that began 2,800 years ago and extended to AD 2000.

The most clearly defined and longest interval of sustained dryness of this history stretched from about AD 850 to AD 1080, coincident with the well-known Medieval Warm Period, while the most extreme wetness interval occurred during the depths of the last stage of the Little Ice Age. Also evident in the two scientists' wetness history was a period of relative dryness centered on about AD 1550, which corresponded to a period of relative warmth that has previously been documented by several other studies. Preceding the Medieval Warm Period, their hydro-climate reconstruction reveals a highly chaotic period of generally greater wetness that corresponds to the Dark Ages Cold Period, while also evident were dryness peaks representing the Roman Warm Period and two other periods of relative dryness located about 500 years on either side of its center.

The correlation this study demonstrates to exist between relative wetness and warmth in Scotland strongly suggests the temperature of the late twentieth century was nowhere near the highest of the past two millennia in that part of the world, as five other periods over the past 2,800 years were considerably warmer. Blundell and Barber cite many studies that report findings similar to theirs throughout much of the rest of Europe and the North Atlantic Ocean.

Linderholm and Gunnarson (2005) developed what they called the Jämtland multi-millennial tree-ring width chronology, derived from living and subfossil Scots pines (*Pinus sylvestris* L.) sampled close to the present tree-line in the central Scandinavian Mountains. This record spanned 2893 BC to AD 2002, with minor gaps at 1633–1650 BC and AD 887–907. The two researchers focused their analysis on the well-replicated period of 1632 BC to AD 2000, utilizing it as a proxy for summer temperatures.

Several periods of anomalously warm and cold summers were noted throughout the record: 550 to 450 BC (Roman Warm Period), when summer temperatures were the warmest of the entire record, exceeding the 1961–1990 mean by more than 6°C; AD 300 to 400 (Dark Ages Cold Period), which was "the longest period of consecutive cold summers," averaging 1.5°C less than the 1961–1990 mean; AD 900 to 1000, a warm era corresponding to the Medieval Warm Period; and AD 1550 to 1900, a cold period known as the Little Ice Age. With respect to the final section of the tree-ring record, which encompasses the period of modern warming, Linderholm and Gunnarson state this phenomenon "does not stand out as an anomalous feature in the 3600-year record," noting "other periods show more rapid warming and also higher summer temperatures."

Berge *et al*. (2005) describe and discuss the significance of what they refer to as "the first observations of settled blue mussels *Mytilus edulis* L. in the high Arctic Archipelago of Svalbard for the first time since the Viking Age." This discovery of the blue mussel colony was made by divers in August and September 2004 at Sagaskjaeret, Isfjorden, Svalbard (78°13'N, 14°E). Subsequent inferences of the five researchers with regard to pertinent regional climatic and oceanographic conditions over the prior few years led them to conclude "the majority of blue mussels were transported as larvae in unusually warm water by the West Spitsbergen Current from the mainland of Norway to Spitsbergen during the summer of 2002." They write "it is highly probable that the newly established blue mussel population is a direct response to a recent increase in sea surface temperatures."

Berge *et al*. further note the "distribution patterns of blue mussels *Mytilus edulis* L. in the high Arctic indicate that this thermophilous mollusk was abundant along the west coast of Svalbard during warm intervals (Salvigsen *et al*., 1992; Salvigsen, 2002) in the Holocene," but mussels of this species "have not been present at Svalbard for the last 1000 years (Salvigsen, 2002)." In light of these well-documented real-world observations, including the fact that blue mussels only recently had begun to reestablish themselves in this part of the world, they

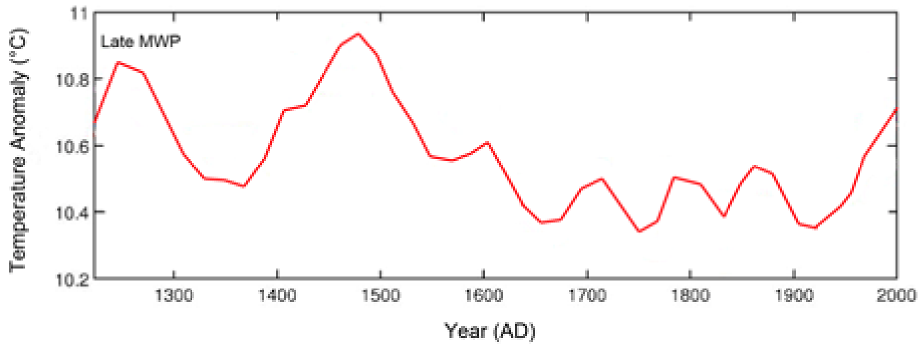

Figure 4.2.4.6.2.1. Decadally smoothed diatom-based temperature reconstruction from Lake Tsuolbmajavri in Finish Lapland. Adapted from Weckstrom, J., Korhola, A., Erasto, P., and Holmstrom, L. 2006. Temperature patterns over the past eight centuries in Northern Fennoscandia inferred from sedimentary diatoms. *Quaternary Research* **66**: 78–86.

conclude water temperatures there were only beginning to "approach those of the mediaeval warm period."

Weckstrom *et al.* (2006) developed a high-resolution quantitative history of temperature variability over the past 800 years, based on analyses of diatoms found in a sediment core retrieved from a treeline lake—Lake Tsuolbmajavri (68°41'N, 22°05'E)—in Finnish Lapland. The work revealed the "termination phase of the MWP," which they indicate as having occurred between AD 1200 and 1300, was 0.15°C warmer than the peak warmth of the Current Warm Period, which in their history occurred at the conclusion of the twentieth century (see Figure 4.2.4.6.2.1).

Eiriksson *et al.* (2006) reconstructed the near-shore thermal history of the North Atlantic Current along the western coast of Europe over the last two millennia, based on measurements of stable isotopes, benthic and planktonic foraminifera, diatoms, and dinoflagellates, as well as geochemical and sedimentological parameters, which they acquired on the Iberian margin, the West Scotland margin, the Norwegian margin, and the North Icelandic shelf. In addition to identifying the Roman Warm Period (nominally 50 BC–AD 400), which exhibited the warmest sea surface temperatures of the last two millennia on both the Iberian margin and the North Icelandic shelf, and the following Dark Ages Cold Period (AD 400–800), Eiriksson *et al.* report detecting the Medieval Warm Period (AD 800–1300) and Little Ice Age (AD 1300–1900), which was followed in some records by a strong warming to the present. They stated the latter warming "does not appear to be unusual when the proxy records spanning the last two millennia are examined."

The results of Eiriksson *et al.*'s research confirm the millennial-scale climatic oscillation that has been responsible for periodically producing centennial-scale warm and cold periods throughout Earth's history. It also reveals there is nothing unusual or unnatural about the Current Warm Period, which in the case of two of their four sites was found to be somewhat cooler than it was during the Roman Warm Period of 2,000 years ago, when the atmosphere's CO_2 concentration was more than 100 ppm less than it is today.

Haltia-Hovi *et al.* (2007) extracted sediment cores from beneath the 0.7-m-thick ice platform on Lake Lehmilampi (63°37'N, 29°06'E) in North Karelia, eastern Finland, in the springs of 2004 and 2005. They identified and counted the approximately 2,000 annual varves contained in the cores and measured their individual thicknesses and mineral and organic matter contents. They compared these climate-related data with residual $\Delta^{14}C$ data derived from tree rings, which serve as a proxy for solar activity. They report their "comparison of varve parameters (varve thickness, mineral and organic matter accumulation) and the activity of the sun, as reflected in residual $\Delta^{14}C$ [data] appears to coincide remarkably well in Lake Lehmilampi during the last 2000 years, suggesting solar forcing of the climate."

In addition, the Finnish researchers state, "the low deposition rate of mineral matter in AD 1060–1280 possibly implies mild winters with a short ice cover period during that time with minor snow accumulation interrupted by thawing periods." They note the low accumulation of organic matter during this period "suggests a long open water season and a high decomposition rate of organic matter." Consequently, since the AD 1060–1280 period shows by far the lowest levels of both mineral and organic matter content (Figure 4.2.4.6.2.2), and since "the thinnest varves of the last 2000 years were deposited during [the] solar activity maxima in the Middle Ages," it is difficult not to conclude the period was likely the warmest of the past two millennia.

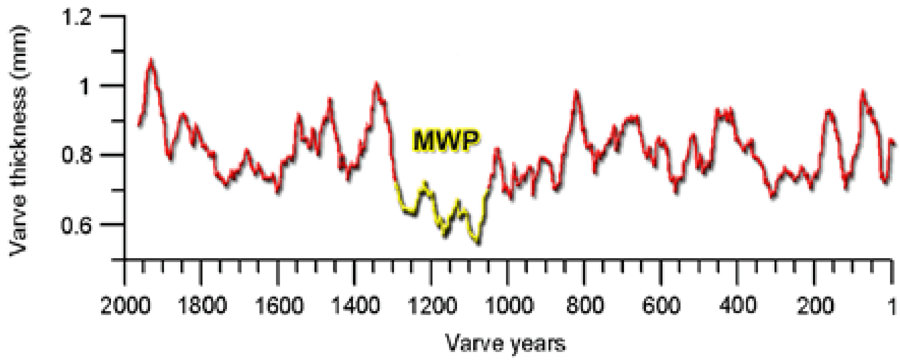

Figure 4.2.4.6.2.2. Varve thickness from sediment cores obtained from Lake Lehmilampi, eastern Finland. Adapted from Haltia-Hovi, E., Saarinen, T., and Kukkonen, M. 2007. A 2000-year record of solar forcing on varved lake sediment in eastern Finland. *Quaternary Science Reviews* **26**: 678–689.

Allen *et al*. (2007) analyzed pollen characteristics within sediment cores retrieved from a small unnamed lake located at 71°02'18"N, 28°10'6.6"E near the coast of Nordkinnhalvoya, Finnmark, Norway and constructed a climatic history of the area. They found "regional vegetation responded to Holocene climatic variability at centennial-millennial time scales" and report, "the most recent widely documented cooling event, the Little Ice Age of ca 450–100 cal BP, also is reflected in our data by a minimum in *Pinus:Betula* [pollen] ratio beginning ca 300 cal BP and ending only in the recent past." They also note, "the Dark Ages cool interval, a period during which various other proxies indicate cooling in Fennoscandia and beyond, is evident too, corresponding to lower values of *Pinus:Betula* [pollen] ratio ca 1600–1100 cal BP." In addition, "the Medieval Warm Period that separated the latter two cool intervals also is strongly reflected in our data, as is the warm period around two millennia ago during which the Roman Empire reached its peak."

Jiang *et al*. (2007) analyzed diatom data they obtained from core MD992271 (66°30'05"N, 19°30'20"W) on the North Icelandic shelf to derive summer sea surface temperatures (SSTs) for that location based on relative abundances of warm and cold water species. They compared the results they obtained with results derived by Jiang *et al*. (2002, 2005) via similar analyses of nearby cores HM107-03 (66°30'N, 19°04'W) and MD992275 (66°33"N, 17°42'W), as well as results derived from GISP2 $\delta^{18}O$ data and other marine sediment records obtained from other regions of the North Atlantic.

The data from the new sediment core revealed a gradually decreasing temperature trend over the entire reconstructed 3,000-year SST record, with superimposed centennial- and millennial-scale summer SST fluctuations. In addition, Jiang *et al*. write, "the Medieval Warm Period and the Little Ice Age are identified in the record," with the former period appearing to have prevailed between approximately AD 950 and 1250. The MD992271 record ended in the midst of the Little Ice Age and therefore did not reveal any nineteenth or twentieth century warming. The HM107-03 record, on the other hand, extended to within about 50 years of the present, but it too showed no evidence of any warming at its end. Core MD992275 extended to the nominal present, however, and it suggested the end of the twentieth century was at least three-quarters of a degree Centigrade cooler than the peak temperature of the Medieval Warm Period, about the same qualitative and quantitative difference suggested by the GISP2 $\delta^{18}O$ data.

Jiang *et al*. note, "comparison of the data from core MD992271 with those from two other cores, HM107-03 and MD992275, on the North Icelandic shelf shows coherent late Holocene changes in reconstructed summer SST values ... reflecting regional changes in the summer SSTs on the North Icelandic shelf." They conclude, "the consistency between changes in the late Holocene summer SSTs on the North Icelandic shelf and in GISP2 $\delta^{18}O$ data, as well as in other marine sediment records from the North Atlantic, further suggests synchronous North Atlantic-wide climate fluctuations."

Justwan *et al*. (2008) reconstructed August sea surface temperatures with a resolution of 40 years over the past 11,000-plus years based on analyses of diatoms found in a sediment core extracted from the northern Icelandic shelf (66°37'53"N, 20°51'16"W). Figure 4.2.4.6.2.3 illustrates the data for the most recent two millennia of this record, showing the peak warmth of the MWP is essentially identical to the peak warmth of the Current Warm Period, albeit the peak warmth of the CWP does not appear at its current endpoint, which would technically make the CWP's current temperature about 0.5°C less than the

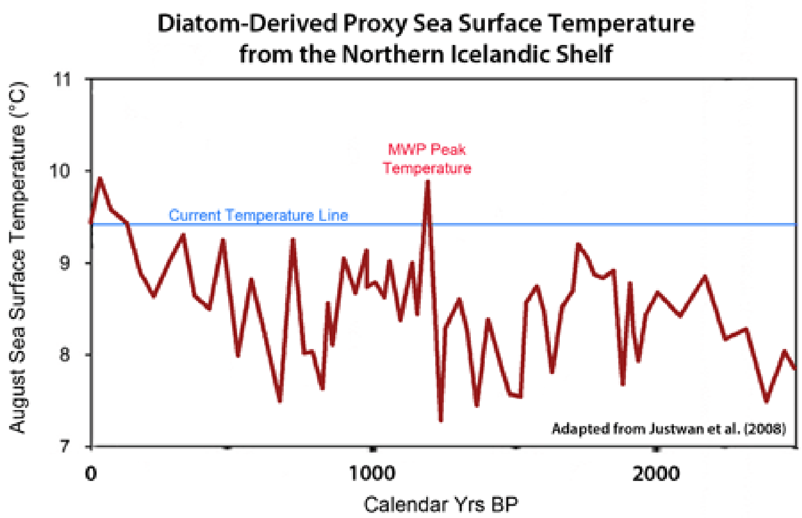

Figure 4.2.4.6.2.3. A diatom-based sea surface temperature reconstruction from the northern Icelandic shelf. Adapted from Justwan, A., Koc, N., and Jennings, A.E. 2008. Evolution of the Irminger and East Icelandic Current systems through the Holocene, revealed by diatom-based sea surface temperature reconstructions. *Quaternary Science Reviews* **27**: 1571–1582.

peak MWP temperature.

Leipe *et al*. (2008) analyzed five 60-cm sediment cores retrieved from the eastern Gotland Basin in the central Baltic Sea (~56°55'–57°15'N, 19°20'–20°00'E) for a variety of physical, chemical, and biological properties. They report, "during the Medieval Warm Period, from about AD 900 to 1250, the hydrographic and environmental conditions were similar to those of the present time." They note, moreover, analyses of lignin compounds in the sediment cores, which "can be used to characterize terrigenous organic matter from plants," pointed to the Medieval Warm Period possibly being warmer than the Current Warm Period.

Sicre *et al*. (2008) developed a unique, 2,000-year-long summer sea surface temperature (SST) record with unprecedented temporal resolution (2–5 years) from a sediment core retrieved off North Iceland (66°33'N, 17°42W), based on their analyses of alkenones synthesized primarily in the summer by the marine alga *Emiliania huxleyi* that grew in the overlying ocean's surface waters, dating the SST data by tephrochronology. Figure 4.2.4.6.2.4 is adapted from the temperature history they derived. Of particular interest is its clear depiction of the millennial-scale oscillation of climate that produced the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period.

In comparing prior temperatures to those of the near-present, the figure shows the SST record peaks at about 8.3°C somewhere around 1940, a particularly warm time in Earth's modern history. However, the researchers show a "modern temperature" of 9°C they determined from a box-core of nearby surface sediment, which they say "is consistent with the recent compilation produced by Hanna *et al.* (2006)." The latter reported, "since 1874, July and August SSTs measured at Grimsey Island have varied between 6.7 and 9°C," which suggests Sicre *et al.*'s 9°C value is the *peak* modern temperature observed in the time of Hanna *et al.*'s analysis. It can be concluded the peak temperature of the Medieval Warm Period was fully 1°C warmer than the peak temperature of the Current Warm Period, and the peak temperature of the Roman Warm Period was about 0.5°C warmer than that of the Current Warm Period.

Grudd (2008) notes many tree-ring-based temperature histories terminate far short of the end of the twentieth century, and he states there is thus "an urgent need to update existing tree-ring collections throughout the northern hemisphere," especially to make valid comparisons of past high-temperature periods, such as the Medieval Warm Period, with the present.

Working with an extensive set of Scots pine (*Pinus sylvestris* L.) tree-ring maximum density (MXD) data from the Torneträsk area of northern Sweden, originally compiled by Schweingruber *et al.* (1988) and covering the period AD 441–1980, Grudd extended the record an additional 24 years to 2004 using new samples obtained from 35 relatively young trees. This had the effect of reducing the mean cambial age of the MXD data in the twentieth century and thus eliminating a disturbing "loss of sensitivity to temperature, apparent in earlier versions of the Torneträsk MXD chronology (Briffa, 2000)." The results are depicted in Figure 4.2.4.6.2.5.

Grudd concluded, as is readily evident from the results presented in the figure above, "the late-twentieth century is not exceptionally warm in the new Torneträsk record," since "on decadal-to-century timescales, periods around AD 750, 1000, 1400 and 1750 were all equally warm, or warmer." He states,

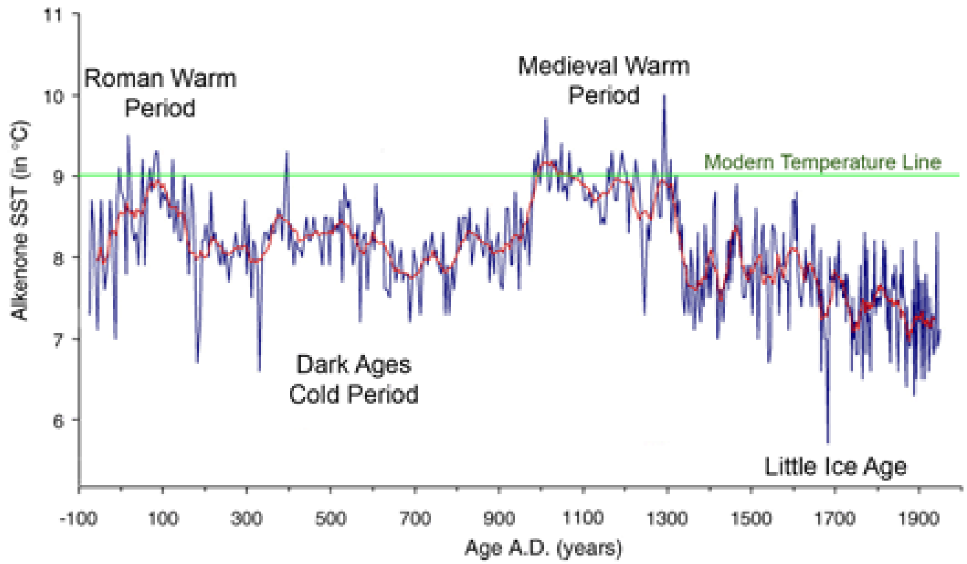

Figure 4.2.4.6.2.4. A 2,000-year summer sea surface temperature record derived from an ocean sediment core off the coast of north Iceland. Adapted from Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L., Jansen, E., and Turon, J.-L. 2008. Decadal variability of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary Science Letters* **268**: 137–142.

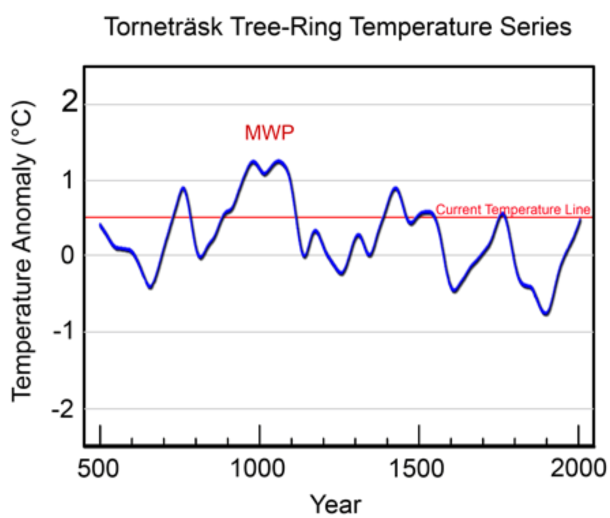

Figure 4.2.4.6.2.5. Tree-ring temperature proxy from Torneträsk, Sweden. Adapted from Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, C., Yiou, P., Eiriksson, J., Knudsen, K.L., Jansen, E., and Turon, J.-L. 2008. Decadal variability of sea surface temperatures off North Iceland over the last 2000 years. *Earth and Planetary Science Letters* **268**: 137–142.

"the warmest summers in this new reconstruction occur in a 200-year period centered on AD 1000," leading him to declare, "Fennoscandia seems to have been significantly warmer during medieval times as compared to the late-twentieth century," and this period "was much warmer than previously recognized." In addition, he notes, "a warm period around AD 1000 is in line with evidence from other proxy indicators from northern Fennoscandia," writing, "pine tree-limit (Shemesh *et al*., 2001; Helama *et al*., 2004; Kulti *et al*., 2006) [and] pollen and diatoms (Korhola *et al*., 2000; Seppa and Birks, 2002; Bigler *et al*., 2006) show indisputable evidence of a 'Medieval Warm Period' that was warmer than the twentieth century climate."

Helama *et al*. (2009) used data obtained from hundreds of moisture-sensitive Scots pine tree-ring records originating in Finland and regional curve standardization (RCS) procedures to develop what they describe as "the first European dendroclimatic precipitation reconstruction," which "covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP)," running from AD 670 to AD 1993. These data, they write, indicate "the special feature of this period in climate history is the distinct and persistent drought, from the early ninth century AD to the early thirteenth century AD," which "precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture." In addition, they report "the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, AD 1220–1650) and the DACP (here, AD 720–930)."

The three Finnish scientists note "the global medieval drought that we found occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook *et al*., 2004, 2007), eastern South America (Stine, 1994; Rein *et al*., 2004), and equatorial East Africa (Verschuren *et al*., 2000; Russell and Johnson, 2005, 2007; Stager *et al*., 2005) between AD 900 and 1300." Noting further "the global evidence argues for a common force behind the hydrological component of the MCA," they report "previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren *et al*., 2000; Stager *et al*., 2005) or the ENSO (Cook *et al*., 2004, 2007; Rein *et al*., 2004; Herweijer *et al*., 2006, 2007; Graham *et al*., 2007, Seager *et al*., 2007)." They conclude, "the evidence so far points to the medieval solar activity maximum (AD 1100–1250), because it is observed in the $\Delta^{14}C$ and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki *et al*., 2004)."

Bjune *et al*. (2009) used mean July temperature reconstructions based on "pollen-stratigraphical data obtained from eleven small lakes located in the middle boreal, northern boreal, low-alpine, or low-arctic zones of northern Norway, northern Sweden, northern Finland and north-west Russia" to develop a mean quantitative temperature history spanning the past two millennia for this Northern Fennoscandia region (66°25'–70°50'N, 14°03'–35°19'E). They report, "no consistent temperature peak is observed during the 'Medieval Warm Period.'" But a graph of their final result (see Figure 4.2.4.6.2.6) shows what they describe as the present temperature (red vertical line)—derived from the uppermost 1 cm of the sediment cores, which were collected at various times between AD 1994 and 2003—is colder than almost all of the data points obtained by the authors over the past 2,000 years. Focusing on the Medieval Warm Period, it is evident temperatures then were as much as 1.4°C warmer than what they were over the most recent decade or so.

Axford *et al*. (2009) write, "the idea of a widespread and spatially coherent 'Medieval Warm Period' (MWP) has come under scrutiny in recent years," but "it remains a viable hypothesis that a period of relative warmth in northwestern Europe and the northern North Atlantic region helped facilitate Norse expansion across the North Atlantic from the ninth to thirteenth centuries, including settlement of Iceland and Greenland," and "subsequent cooling contributed to the demise of the Norse settlements on Greenland." They developed a regional climatic record from a sediment core retrieved from lake Stora Vioarvatn in northeast Iceland (66°14.232'N, 15°50.083'W) in the summer of 2005, based on chironomid assemblage data, which were well correlated with nearby measured temperatures over the 170-year instrumental record, and total organic carbon, nitrogen, and biogenic silica content.

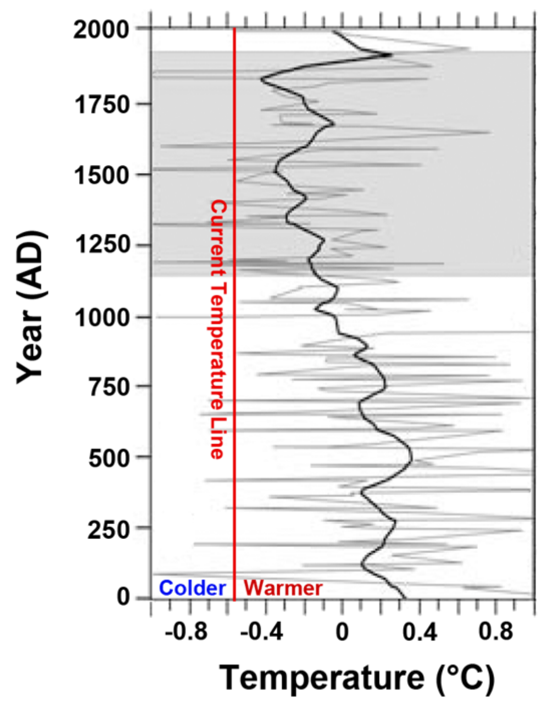

Figure 4.2.4.6.2.6. Mean July temperature reconstruction based on pollen-stratigraphical data obtained from eleven small lakes located in the boreal and alpine low-arctic zones of northern Norway, northern Sweden, northern Finland and north-west Russia. Adapted from Bjune, A.E., Seppa, H., and Birks, H.J.B. 2009. Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *Journal of Paleolimnology* **41**: 43–56.

The four researchers report their data indicated "warm temperatures in the tenth and eleventh centuries, with one data point suggesting temperatures slightly warmer than present." They also found "temperatures were higher overall and more consistently high through much of the first millennium AD" (see Figure 4.2.4.6.2.7).

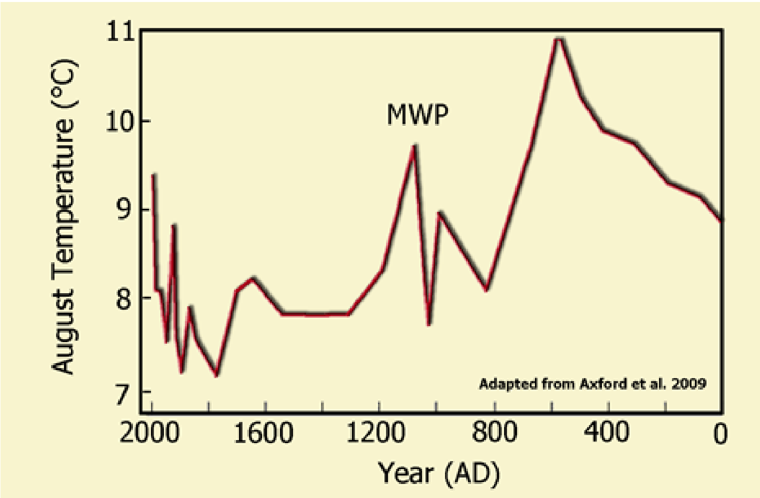

Figure 4.2.4.6.2.7. August temperature reconstruction from Lake Stora Vioarvatn. Adapted from Axford, Y., Geirsdottir, A., Miller, G.H., and Langdon, P.G. 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. *Journal of Paleolimnology* **41**: 7–24.

The Icelandic, UK and U.S. scientists write, "the historical perception of a significant medieval climate anomaly in Iceland may be primarily a reflection of the human perspective," in that "Iceland was settled ca. AD 870, during a period of relative warmth that was followed by many centuries of progressively colder and less hospitable climate." They also note, "had the Norse settled Iceland 1000 years earlier, the MWP might be viewed only as a brief period of climatic amelioration, a respite from a shift to colder temperatures that began in the eighth century," near the end of several centuries of even greater warmth. Viewed from either perspective, it is clear there is nothing unusual or unnatural about the region's present-day temperatures, which the researchers say "do not show much recent warming."

Stancikaite *et al*. (2009) carried out inter-disciplinary research at the Impiltis hill fort and settlement area of Northwest Lithuania "to study the climate and the human impact on the landscape, the development of the settlement and the hill fort, the types of agriculture employed there, and changes in the local economy." They determined "the transition from the first to the second millennium AD, also the onset of the 'Medieval Warm Period,' coincided with a period of intensive human activity at the Impiltis hill fort and settlement area."

There was at that time, they discovered, "a high intensity of farming activities, which were supported by favorable climatic conditions and included the existence of permanent agricultural fields as well as the earliest record of rye cultivation in NW Lithuania." The "period of most prominent human activity in the Impiltis," as the eight researchers describe it, "was dated back to about 1050–1250 AD," when they suggest "the favorable climatic conditions of [this] 'Medieval Warm Period' may have supported human activity during its maximum phase." This inference, they write, "correlates well with the chronology of the hill fort and settlement prosperity as represented in data collected from the site." Thereafter, they further suggest, "it is possible that the ensuing gradual regression of human activity was caused, in part, by the climatic deterioration known as the 'Little Ice Age.'"

Bonnet *et al*. (2010) developed a high-resolution record of ocean and climate variations during the late Holocene in the Fram Strait (the major gateway between the Arctic and North Atlantic Oceans, located north of the Greenland Sea), using detailed analyses of a sediment core recovered from a location (78°54.931'N, 6°46.005'E) on the slope of the western continental margin of Svalbard, based on analyses of organic-walled dinoflagellate cysts that permit the reconstruction of sea-surface conditions in both summer and winter. The latter reconstructions, they write, "were made using two different approaches for comparison and to insure the robustness of estimates." These were "the modern analogue technique, which is based on the similarity degree between fossil and modern spectra" and "the artificial neural network technique, which relies on calibration between hydrographical parameters and assemblages."

Bonnet *et al*. discovered the sea surface temperature (SST) histories they developed were "nearly identical and show oscillations between -1°C and 5.5°C in winter and between 2.4°C and 10.0°C in summer." Their graphical results show between 2,500 and 250 years before present (BP), the mean SSTs of summers were warmer than those of the present about 80 percent of the time, and the mean SSTs of winters exceeded those of current winters approximately 75 percent of the time, with the long-term (2,250-year) means of both seasonal periods averaging about 2°C more than current means. In addition, the highest temperatures were recorded around 1,320 cal. years BP, during a warm interval that persisted from about AD 500 to 720 during the very earliest stages of the Medieval Warm Period (MWP), when the peak summer and winter temperatures exceeded the peak summer and winter temperatures of the first several years of the twenty-first century by about 3°C.

Haltia-Hovi *et al*. (2010) write, "lacustrine sediment magnetic assemblages respond sensitively to environmental changes," and "characteristics of magnetic minerals, i.e. their concentration, mineralogy and grain size in sediments, can be studied by making mineral magnetic measurements, which yield large quantities of environmental data rapidly and non-destructively," citing Evans and Heller (2003). Working with two sediment cores taken from Finland's Lake Lehmilampi (63°37'N, 29°06'E), they constructed detailed chronological histories of several magnetic properties of the sediments, as well as a history of their total organic carbon content.

The four researchers discovered a "conspicuous occurrence of fine magnetic particles and high organic concentration" evident around 4,700–4,300 Cal. yrs BP. This period, they note, "is broadly coincident with glacier contraction and treelines higher than present in the Scandinavian mountains according to Denton and Karlen (1973) and Karlen and Kuylenstierna (1996)." From that time on toward the present, there was a "decreasing trend of magnetic concentration, except for the slight localized enhancement in the upper part of the sediment column at ~1,100–900 Cal. yrs BP," where the year zero BP = AD 1950.

Changes of these types have been attributed in prior studies to magnetotactic bacteria (e.g. *Magneto-spirillum* spp.), which Haltia-Hovi *et al*. describe as "aquatic organisms that produce internal, small magnetite or greigite grains" that are used "to navigate along the geomagnetic field lines in search of micro or anaerobic conditions in the lake bottom," as described by Blakemore (1982) and Bazylinski and Williams (2007). They further note the studies of Snowball (1994), Kim *et al*. (2005), and Paasche *et al*. (2004) "showed magnetic concentration enhancement, pointing to greater metabolic activity of these aquatic organisms in the presence of abundant organic matter," which is also what Haltia-Hovi *et al*. The latter scientists report the "concentration of organic matter in the sediment is highest, together with fine magnetic grain sizes, in the time period 1,100–900 Cal. years BP," and they say this time interval "is associated with warmer temperatures during the Medieval Climate Anomaly according to the varve parameters of Lake Lehmilampi," citing the precise core-dating by varve-counting work of Haltia-Hovi *et al*. (2007). Taken together, these observations strongly suggest the peak warmth of the Medieval Warm Period (about AD 850–1050) was very likely somewhat greater than that of the Current Warm Period.

Luoto and Helama (2010) analyzed a sediment core extracted in October 2008 from Lake Pieni-Kauro in eastern Finland (64°17'N, 30°07'E), identifying and quantifying midge assemblages dominated by chironomids. They reconstructed a 1,500-year history of mean July air temperature from the Finnish multi-lake calibration model of Luoto (2009). The results, depicted in Figure 4.2.4.6.2.8, delineate a Medieval Warm Period stretching from about AD 580 to 1280, the peak temperature of which was approximately 0.3°C greater than the peak temperature at the end of the record, which concludes near the end of 2008.

Sundqvist *et al*. (2010) developed a 4,000-year $\delta^{18}O$ history from a stalagmite (K11) they collected in 2005 from Korallgrottan, a cave in the Caledonian mountain range of Jamtland County, northwest Sweden (64°53'N, 14°E). As shown in Figure 4.2.4.6.2.9, they demonstrated the $\delta^{18}O$ history to be well correlated with temperature, even that of the entire Northern Hemisphere.

In describing the $\delta^{18}O$ history, Sundqvist *et al*. write, "the stable isotope records show enriched isotopic values during the, for Scandinavia, comparatively cold period AD 1300–1700 [which they equate with the Little Ice Age] and depleted values during the warmer period AD 800–1000 [which they equate with the Medieval Warm Period]." As can clearly be seen from their figure, the two $\delta^{18}O$ depletion "peaks" (actually inverted valleys) of the Medieval Warm Period are both more extreme than the "peak" value of the Current Warm Period, which appears at the end of the record.

Gunnarson *et al*. (2011) write, "dendro-climatological sampling of Scots pine (*Pinus sylvestris* L.) has been made in the province of Jamtland, in the west-central Scandinavian mountains, since the 1970s," and "a maximum latewood density (MXD) dataset, covering the period

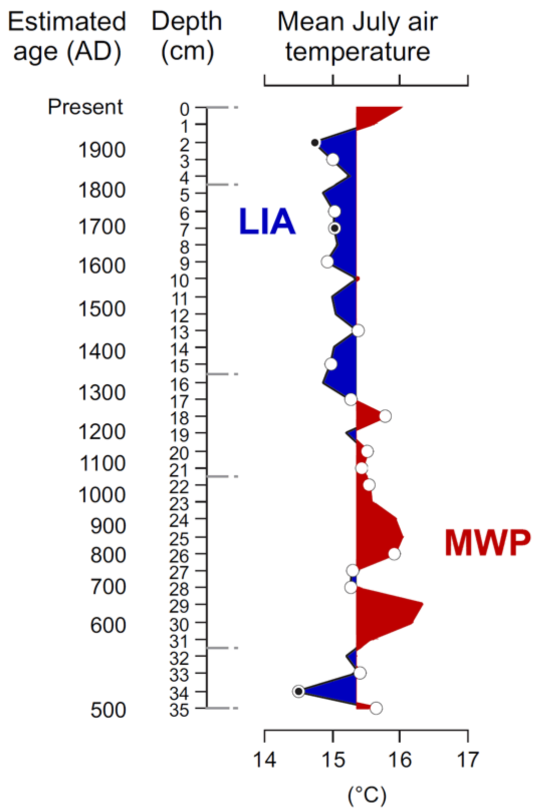

Figure 4.2.4.6.2.8. Reconstructed mean July air temperature from Lake Pieni-Kauro in eastern Finland. Adapted from Luoto, T.P. and Helama, S. 2010. Palaeoclimatological and palaeolimnological records from fossil midges and tree-rings: the role of the North Atlantic Oscillation in eastern Finland through the Medieval Climate Anomaly and Little Ice Age. *Quaternary Science Reviews* **29**: 2411–2423.

AD 1107–1827 (with gap 1292–1315) was presented in the 1980s by Fritz Schweingruber." Gunnarson *et al*. combined these older historical MXD data with "recently collected MXD data covering AD 1292–2006 into a single reconstruction of April–September temperatures for the period AD 1107–2006," using regional curve standardization (RCS), which "provides more low-frequency variability than 'non-RCS' and stronger correlation with local seasonal temperatures."

The three researchers found "a steep increase in inferred temperatures at the beginning of the twelfth century, followed by a century of warm temperatures (ca. 1150–1250)," which falls within the temporal confines of the Medieval Warm Period, and they state, "the record ends with a sharp increase in temperatures from around 1910 to the 1940s, followed by decreasing temperatures for a few decades," after which, they indicate, "another sharp increase in April–September temperature commenced in the late 1990s," during what is commonly known as the Current Warm Period. They conclude "the two warmest periods are the mid to late twentieth century and the period from AD 1150–1250," emphasizing the temperatures of both periods have been so similar that "it is not possible to conclude whether the present and relatively recent past are warmer than the 1150–1250 period."

Divine *et al*. (2011) write, "the recent rapid climate and environmental changes in the Arctic, for instance, sea-ice retreat (e.g., Comiso *et al*., 2008) and ice-sheet melting (e.g., van den Broeke *et al*., 2009), require a focus on long-term variability in this area in order to view these recent changes in the long-term context." Working with ice cores extracted from Svalbard at Lomonosovfonna in 1997 (Isaksson *et al*., 2001) and at Holtedahlfonna in 2005 (Sjorgren *et al*., 2007), Divine *et al*. used the $\delta^{18}O$ data derived from them to reconstruct 1,200-year winter (Dec–Feb) surface air temperature histories for nearby Longyearbyen (78.25°N, 15.47°E) and farther-afield Vardo (70.54°N, 30.61°E, in northern Norway), by calibrating (scaling) the $\delta^{18}O$ data to corresponding historically observed tempera-tures at the two locations, which for Longyearbyen were first collected in 1911 and for Vardo have been extended back to 1840 as a result of the work of Polyakov *et al*. (2003).

These efforts resulted in the winter surface air temperature reconstructions depicted in Figure 4.2.4.6.2.10, which begin at the peak warmth of the Medieval Warm Period at a little before AD 800. Temperatures thereafter decline fairly steadily to the coldest period of the Little Ice Age at about AD 1830, after which they rise into the 1930s, decline, and then rise again, terminating just slightly lower than their 1930s peaks near the end of the 1990s. The 11-year running-mean peak winter temperature of the Medieval Warm Period was approximately 9°C greater than the end-of-record 11-year running-mean peak winter temperature at Longyearbyen, whereas it was about 3.3°C warmer at Vardo.

Velle *et al*. (2011) used two short gravity cores and two long piston cores of sediments obtained from the deepest part of Lake Skardtjorna, Spitsbergen (77°57.780'N, 13°48.799'E) in 2008, plus a long core obtained in 2003, to reconstruct histories of chironomid types and concentrations over the past 2,000 years. They translated the chironomid data into

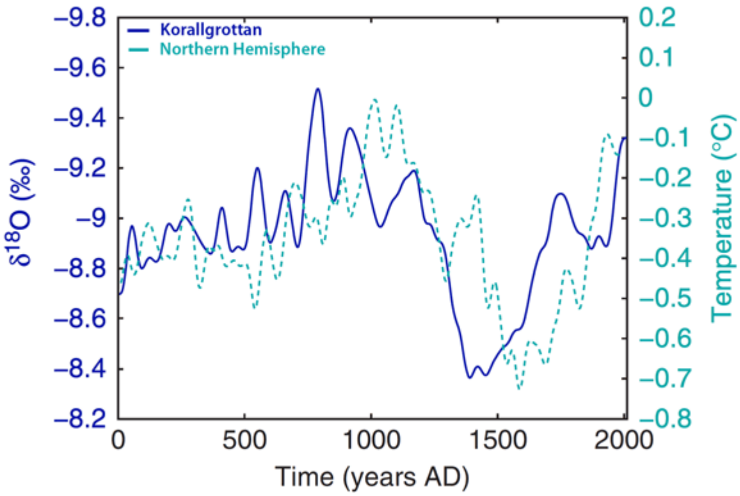

Figure 4.2.4.6.2.9. The 2,000-year Northern Hemispheric temperature reconstruction (dashed line) of Moberg *et al*. (2005) and the last half of the $\delta^{18}O$ history (solid line) developed from the K11 stalagmite. Adapted from Sundqvist, H.S., Holmgren, K., Moberg, A., Spotl, C., and Mangini, A. 2010. Stable isotopes in a stalagmite from NW Sweden document environmental changes over the past 4000 years. *Boreas* **39**: 77–86.

mean July air temperatures based on a modern mean July air temperature calibration dataset compiled by Brooks and Birks (2000, 2001), plus additional unpublished data for 2001–2009, utilizing new approaches they developed for their paper. The two researchers write, a "warming that occurred at 1000 to 830 BP," where BP = 2003, "may correspond to what is known as the 'Medieval Warm Period.'" Their graphical representation of that record indicates the peak warmth of the MWP can be estimated to be about 0.3°C greater than the peak warmth of the Current Warm Period.

Esper *et al*. (2012) note millennial-length temperature reconstructions have become "an important source of information to benchmark climate models, detect and attribute the role of natural and anthropogenic forcing agents, and quantify the feedback strength of the global carbon cycle." The four researchers developed 587 high-resolution wood density profiles (Frank and Esper, 2005) from living and sub-fossil *Pinus sylvestris* trees of northern Sweden and Finland to form a long-term maximum latewood density (MXD) record from 138 BC to AD 2006, in which all MXD measurements were derived from high-precision X-ray radiodensitometry, as described by Schweingruber *et al*. (1978), and where biological age trends inherent to the MXD data were removed using regional curve standardization (RCS), as described by Esper *et al*. (2003). The new MXD record was calibrated against mean June–August temperatures obtained from the long-term (1876–2006) instrumental records of Haparanda, Karasjok, and Sodankyla. Comparing their results with the earlier temperature reconstructions

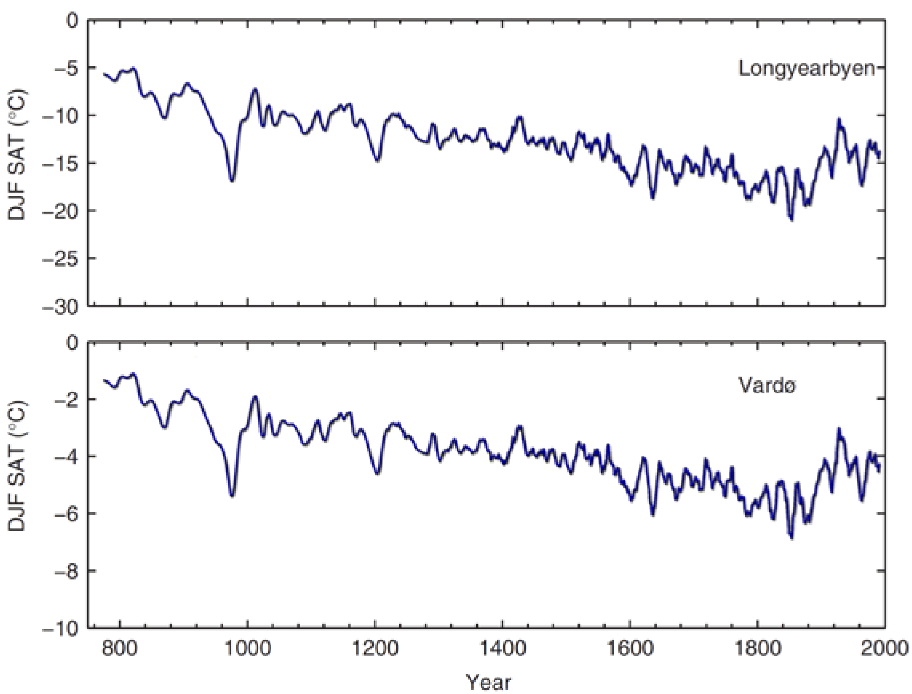

Figure 4.2.4.6.2.10. Reconstructed winter surface air temperature (SAT) for Longyearbyen (top) and Vardo (bottom) vs. time. Adapted from Divine, D., Isaksson, E., Martma, T., Meijer, H.A.J., Moore, J., Pohjola, V., van de Wal, R.S.W., and Godtliebsen, F. 2011. Thousand years of winter surface air temperature variations in Svalbard and northern Norway reconstructed from ice-core data. *Polar Research* **30**: 10.3402/polar.v30i0.7379.

of others, they say their MXD-based summer temperature reconstruction "sets a new standard in high-resolution palaeoclimatology," as "the record explains about 60% of the variance of regional temperature data, and is based on more high-precision density series than any other previous reconstruction." The four researchers report their new temperature history "provides evidence for substantial warmth during Roman and Medieval times, larger in extent and longer in duration than 20th century warmth."

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4.2.4.6.3 Southern

Was there a global Medieval Warm Period? The IPCC used to acknowledge there was, but it has long since changed its view on the subject. Mounting evidence suggests it was wrong to do so. This section describes and discusses data from Southern Europe that support the IPCC's original position.

Martinez-Cortizas *et al*. (1999) analyzed a 2.5 meters-long core from the peat bog of Penido Vello in northwest Spain (43°32'N, 7°34'W), sampled at intervals of 2 cm in the upper 1 meter and at intervals of 5 cm below that depth, to derive a record of mercury deposition that extends to 4,000 radiocarbon years before the present. This work revealed "that cold climates promoted an enhanced accumulation and the preservation of mercury with low thermal stability, and warm climates were characterized by a lower accumulation and the predominance of mercury with moderate to high thermal stability." Based on these findings and further analyses, they derived a temperature history for the region standardized to the mean temperature of the most recent 30 years of their record.

As depicted in Figure 4.2.4.6.3.1, the mean temperature of the Medieval Warm Period in northwest Spain was 1.5°C warmer than it was over the period 1968–1998, and the mean temperature of the Roman Warm Period was 2°C warmer. They also found several decadal-scale intervals during the Roman Warm Period were more than 2.5°C warmer

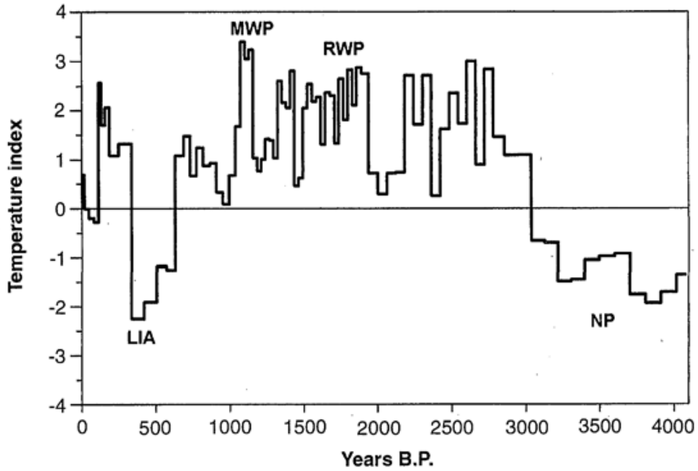

Figure 4.2.4.6.3.1. Temperature proxy for Penido Vello in northwest Spain covering the past 4,000 years. Adapted from Martinez-Cortizas, A., Pontevedra-Pombal, X., Garcia-Rodeja, E., Novoa-Muñoz, J.C., and Shotyk, W. 1999. Mercury in a Spanish peat bog: archive of climate change and atmospheric metal deposition. *Science* **284**: 939–942.

than the 1968–1998 period, and an interval in excess of 80 years during the Medieval Warm Period was more than 3°C warmer. Martinez-Cortizas *et al.* conclude "for the past 4000 years ... the Roman Warm Period and the Medieval Warm Period were the most important warming periods."

Desprat *et al.* (2003) studied the climatic variability of the last three millennia in northwest Iberia via a high-resolution pollen analysis of a sediment core retrieved from the central axis of the Ria de Vigo (42°14.07'N, 8°47.37'W) in the south of Galicia. The results suggest over the past 3,000 years there was "an alternation of three relatively cold periods with three relatively warm episodes." In order of their occurrence, these periods are described by Desprat *et al.* as the "first cold phase of the Subatlantic period (975–250 BC)," which was "followed by the Roman Warm Period (250 BC–450 AD)," and then by "a successive cold period (450–950 AD), the Dark Ages," which "was terminated by the onset of the Medieval Warm Period (950–1400 AD)." That was followed by "the Little Ice Age (1400–1850 AD), including the Maunder Minimum (at around 1700 AD)," which "was succeeded by the recent warming (1850 AD to the present)."

Desprat *et al.* conclude the "solar radiative budget and oceanic circulation seem to be the main mechanisms forcing this cyclicity in NW Iberia," noting "a millennial-scale climatic cyclicity over the last 3,000 years is detected for the first time in NW Iberia paralleling global climatic changes recorded in North Atlantic marine records (Bond *et al.*, 1997; Bianchi and McCave, 1999; Chapman and Shackelton, 2000)."

Silenzi *et al.* (2004) acquired from the northwest coast of Sicily near Capo Gallo promontory new oxygen isotopic data on sea climate trend fluctuations on Vermetid (*Dendropoma petraeum*) reefs that could be interpreted as sea surface temperature (SST) variations. These data clearly depict the Little Ice Age (LIA), with a "temperature variation of about $\Delta T = 1.99 \pm 0.37$ °C between the LIA and present day." Of this period, they write, "Watanabe *et al.* (2001) report that 'seawater temperature records from marine biogenic carbonate including coral and foraminifera all indicate that tropical ocean temperatures were lower by anywhere from 0.5° to 5°C during the LIA (Druffel, 1982; Glynn *et al.*, 1983; Dunbar *et al.*, 1994; Linsley *et al.*, 1994; Keigwin, 1996; Winter *et al.*, 2000) with the vast majority of studies indicating a 1–2°C change.'"

Following the LIA, the data of Silenzi *et al.* reveal what they call "the warming trend that characterized the last century." They note, "this rise in temperature ended around the years 1930–1940 AD, and was followed by a relatively cold period between the years 1940 and 1995." Their data also indicate that in the early to mid-1500s, SSTs were warmer than they are currently, as also has been found to be the case by Keigwin (1996) and McIntyre and McKitrick (2003).

Silenzi *et al.*'s results indicate the Little Ice Age was significantly colder than what is shown by the flawed Northern Hemisphere temperature history of Mann *et al.* (1998, 1999). Moreover, Silenzi *et al.* do not show any sign of the dramatic late twentieth century warming claimed by Mann *et al.* And the work of Silenzi *et al.* indicates temperatures in the early to mid-1500s were warmer than they are currently, whereas Mann *et al.* claim it is currently warmer than it has been at any time over the past millennium or two (Mann and Jones, 2003).

Kvavadze and Connor (2005) present "some observations on the ecology, pollen productivity and Holocene history of *Zelkova carpinifolia*s," a warmth-loving tree whose pollen "is almost always accompanied by elevated proportions of thermophilous taxa," to refine our understanding of Quaternary climatic trends. The discovery of the tree's fossil remains in Holocene sediments, they write, "can be a good indicator of optimal climatic conditions."

The two researchers report, "Western Georgian pollen spectra of the Subatlantic period show that the period began [about 2580 cal yr BP] in a cold phase, but, by 2200 cal yr BP, climatic amelioration commenced," and "the maximum phase of warming [was] observed in spectra from 1900 cal yr BP," and this interval of warmth was Georgia's contribution to the Roman Warm Period. Thereafter, a cooler phase of climate, during the Dark Ages Cold Period, "occurred in Western Georgia about 1500–1400 cal yr BP," but it too was followed by another warm era "from 1350 to 800 years ago," the Medieval Warm Period. During portions of this time interval, they write, tree lines "migrated upwards and the distribution of *Zelkova* broadened." They also present a history of Holocene oscillations of the upper tree-line in Abkhasia, derived by Kvavadze *et al*. (1992), that depicts slightly greater-than-1950 elevations during a portion of the Medieval Warm Period and much greater extensions above the 1950 tree-line during parts of the Roman Warm Period. After the Medieval Warm Period, they report, "subsequent phases of climatic deterioration (including the Little Ice Age) ... saw an almost complete disappearance of *Zelkova* from Georgian forests."

Thus both the Roman and Medieval Warm Periods have been identified in various parts of European Georgia via studies of *Zelkova carpinifolia* pollen found in local sediments, and portions of these warm climatic intervals were likely even warmer than the conditions there during ~AD 1950, which is the "present" of Kvavadze and Connor's study.

Sea surface temperatures, river discharge, and biological productivity were reconstructed by Abrantes *et al*. (2005) in a multi-proxy analysis of a high-resolution sediment core obtained from the Tagus River estuary near Lisbon, Portugal (~ 38.56°N, 9.35°W). The MWP was identified as occurring between AD 550 and 1300, during which mean sea surface temperatures were between 1.5 and 2°C higher than the mean value of the past century, while peak MWP warmth was about 0.9°C greater than late twentieth century peak warmth.

Pla and Catalan (2005) analyzed chrysophyte cyst data collected from 105 lakes in the Central and Eastern Pyrenees of northeast Spain to produce a history of winter/spring temperatures in this region throughout the Holocene. They found a significant oscillation in the winter/spring temperature reconstruction in which the region's climate alternated between warm and cold phases over the past several thousand years. Of particular note were the Little Ice Age, Medieval Warm Period, Dark Ages Cold Period, and Roman Warm Period, and the warmest of these intervals was the Medieval Warm Period, which started around AD 900 and was about 0.25°C warmer than it is currently (Figure 4.2.4.6.3.2).

After the Medieval Warm Period, temperatures fell to their lowest values of the entire record (about 1.0°C below present), after which they began to warm

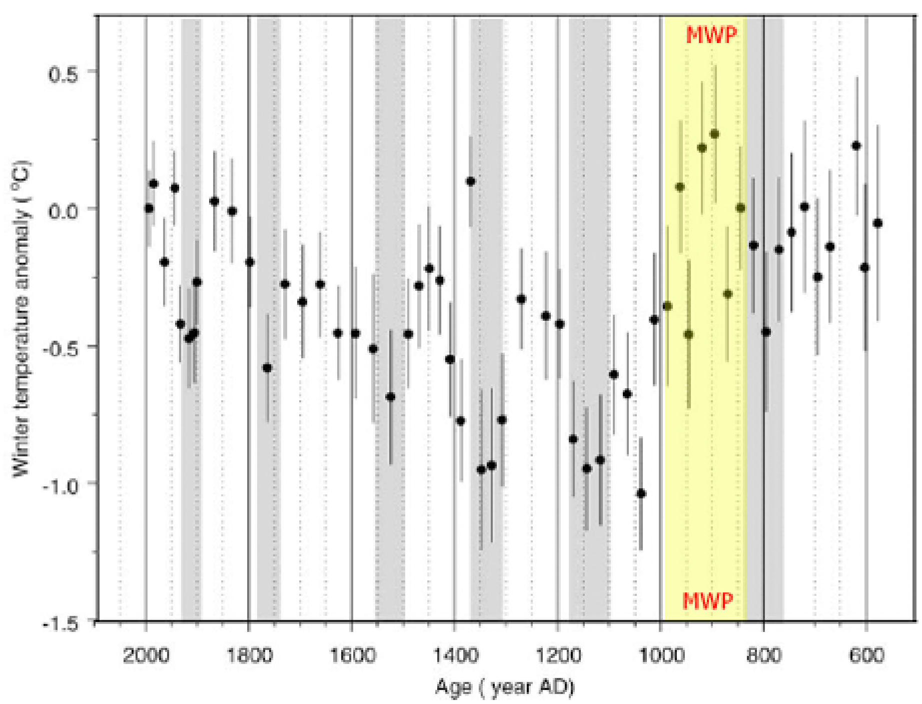

Figure 4.2.4.6.3.2. Altitude anomaly reconstruction from a chrysophyte record converted into winter/spring mean temperatures for the last 1,500 years. Adapted from Pla, S. and Catalan, J. 2005. Chrysophyte cysts from lake sediments reveal the submillennial winter/spring climate variability in the northwestern Mediterranean region throughout the Holocene. *Climate Dynamics* **24**: 263–278.

but remained below present-day values until the early nineteenth and twentieth centuries, with one exception. A significant warming was observed between 1350 and 1400, when temperatures rose a full degree Celsius to a value about 0.15°C warmer than the present. Further examination of Pla and Catalan's data reveals the Current Warm Period is not yet (and may never be) as warm as the Medieval Warm Period, for modern temperatures peaked in the 1970s–1980s and then declined throughout the 1990s.

Giraudi (2005) studied properties of alternating layers of organic-matter-rich soils and alluvial, glacial, and periglacial sediments on higher Apennine massifs in Italy, located at approximately 42°23'N, 13°31'E, reconstructing a history of relative changes in temperature for this region over the past 6,000 years. He determined organic-matter-rich soils formed on slopes currently subject to periglacial and glacial processes around 5740–5590, 1560–1370 and 1300–970 cal yr BP. Based on current relationships between elevation and soil periglacial and glacial processes, Giraudi estimates the mean annual temperature during these three periods "must therefore have been higher than at present," and winter temperatures were at least 0.9-1.2°C higher than those of today.

Cini Castagnoli *et al*. (2005) extracted a $\delta^{13}C$ profile of *Globigerinoides rubber* from a shallow-water core in the Gulf of Taranto off the Italian coast (39°45'53"N, 17°53'33"E), which they used to produce a high-precision record of climate variability over the past two millennia. This record was statistically analyzed, together with a second two-millennia-long tree-ring record obtained from Japanese cedars (Kitagawa and Matsumoto, 1995), for evidence of recurring cycles, using Singular Spectrum Analysis and Wavelet Trans-form, after which both records were compared with a 300-year record of sunspots.

Plots of the pair of two-thousand-year series revealed the existence of the Dark Ages Cold Period (~400–800 AD), Medieval Warm Period (~800–1200 AD), Little Ice Age (~1500–1800 AD), and Current Warm Period. The roots of the latter period can be traced to an upswing in temperature that began in the depths of the Little Ice Age "about 1700 AD." In addition, the statistical analyses showed a common 11-year oscillation in phase with the Schwabe cycle of solar activity, plus a second multidecadal oscillation (of about 93 years for the shallow-water *G. rubber* series and 87 years for the tree-ring series) in phase with the amplitude modulation of the sunspot number series over the past 300 years.

The three researchers state the overall phase agreement between the two climate reconstructions and the variations in the sunspot number series "favors the hypothesis that the [multidecadal] oscillation revealed in $\delta^{13}C$ from the two different environments is connected to the solar activity." This is further evidence for a solar forcing of climate at decadal and multidecadal time scales, as well as for the millennial-scale oscillation of climate that likely has been responsible for the twentieth century warming of the globe that ended the Little Ice Age and ushered in the Current Warm Period.

Frisia *et al*. (2005), working with stalagmite SV1 from Grotta Savi—a cave located at the southeast margin of the European Alps in Italy (45°37'05" N, 13°53'10" E)—developed a 17,000-year record of speleothem calcite $\delta^{18}O$ data, which they calibrated against "a reconstruction of temperature anomalies in the Alps" developed by Luterbacher *et al*. (2004) for the last quarter of the past millennium. This work revealed the occurrence of the Roman Warm Period and a Medieval Warm Period that was broken into two parts by an intervening central cold period. The five researchers state both parts of the Medieval Warm Period were "characterized by temperatures that were similar to the present." As to the Roman Warm Period, they state, its temperatures "were similar to those of today or even slightly warmer."

Garcia *et al*. (2007) note "despite many studies that have pointed to ... the validity of the classical climatic oscillations described for the Late Holocene (Medieval Warm Period, Little Ice Age, etc.), there is a research line that suggests the non-global signature of these periods (IPCC, 2001; Jones and Mann, 2004)." Noting "the best way to solve this controversy would be to increase the number of high-resolution records covering the last millennia and to increase the spatial coverage of these records," they identified five distinct climatic stages: "a cold and arid phase during the Subatlantic (Late Iron Cold Period, < B.C. 150), a warmer and wetter phase (Roman Warm Period, B.C. 150–A.D. 270), a new colder and drier period coinciding with the Dark Ages (A.D. 270–900), the warmer and wetter Medieval Warm Period (A.D. 900–1400), and finally a cooling phase (Little Ice Age, >A.D. 1400)."

Noting "the Iberian Peninsula is unique, as it is located at the intersection between the Mediterranean and the Atlantic, Europe and Africa, and is consequently affected by all of them," Garcia *et al*. suggest "the classical climatic oscillations described for the Late Holocene (Medieval Warm Period, Little Ice Age, etc.)" were both real and global in scope. In addition, the Medieval Warm Period "is identified at about a similar date all around the world (China: Chu *et al*., 2002; Arabia, Fleitmann *et al*., 2004; Africa: Filippi and Talbot, 2005; Iceland: Doner, 2003; central Europe: Filippi *et al*., 1999; New Guinea: Haberle and David, 2004; USA: Cabaniss Pederson *et al*., 2005: Argentina: Mauquoy *et al*., 2004; etc.," the six scientists state, and "comparable changes are described by Desprat *et al*. (2003), Julia *et al*. (1998) and Riera *et al*. (2004) in northwest, central and northeast Spain."

In a paper published in *Science*, Trouet *et al*. (2009) explain how they constructed a 947-year history (AD 1049–1995) of the North Atlantic Oscillation (NAO) using a tree-ring-based drought reconstruction for Morocco (Esper *et al*., 2007) and a speleothem-based precipitation proxy for Scotland (Proctor *et al*., 2000). This history begins in the midst of what they call the Medieval Climate Anomaly (MCA), which they describe as "a period (~AD 800–1300) marked by a wide range of changes in climate globally," and this interval of medieval warmth is "the most recent natural counterpart to modern warmth and can therefore be used to test characteristic patterns of natural versus anthropogenic forcing."

The results of their work are portrayed in Figure 4.2.4.6.3.3, which indicates the peak strength of the NAO during the MCA was essentially equivalent to the peak strength the NAO has so far experienced during the Current Warm Period (CWP), suggesting the peak warmth of the MCA also was likely equivalent to the peak warmth of the CWP.

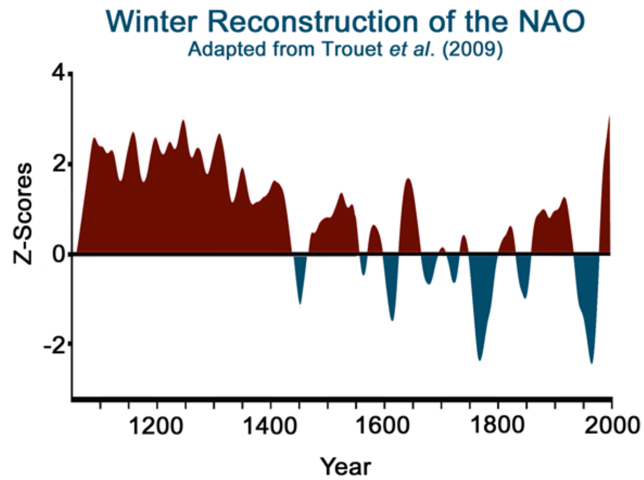

Figure 4.2.4.6.3.3. Winter reconstruction of the NAO over the past 1,000 years. Adapted from Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., and Frank, D.C. 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. *Science* **324**: 78–80.

With respect to what caused the development of medieval warmth throughout Europe, Trouet *et al*. write "the increased pressure difference between the Azores High and the Icelandic Low during positive NAO phases results in enhanced zonal flow, with stronger westerlies transporting warm air to the European continent," to which they add, "stronger westerlies associated with a positive NAO phase may have enhanced the Atlantic meridional overturning circulation (AMOC)," which in turn may have generated "a related northward migration of the intertropical convergence zone."

As for what might have initiated these phenomena, Trouet *et al*. say "the persistent positive phase [of the NAO] reconstructed for the MCA appears to be associated with prevailing La Niña-like conditions possibly initiated by enhanced solar irradiance and/or reduced volcanic activity and amplified and prolonged by enhanced AMOC." That explanation is highly plausible, especially in light of the many paleoclimate studies that have identified cyclical solar activity as the primary cause of various climate cycles (see Chapter 3, this volume). The six scientists conclude, "the relaxation from this particular ocean-atmosphere state [that of the MCA] into the Little Ice Age appears to be globally contemporaneous and suggests a notable and persistent reorganization of large-scale oceanic and atmospheric circulation patterns." Consequently, it is equally reasonable to suggest the reversal of this process—the reinstatement of the particular ocean-atmosphere state that characterized the MCA—may be what has led to the globally contemporaneous development of the Current Warm Period. This scenario suggests the planet's current level of relative warmth may be due to processes originating in the Sun, which are of course not attributable to man.

Geirsdottir *et al*. (2009) studied biogenic silica (BSi) and total organic carbon (TOC) data obtained from two sediment cores retrieved from Haukadalsvatn (65°03.064'N, 21°37.830'W), a lake in northwest Iceland, and a 170-year instrumental temperature history obtained from Stykkisholmur (50 km distant). They identified "a broad peak in BSI and lack of a trend in TOC between ca. 900 and 1200 AD," which they describe as being indicative of "a broad interval of warmth" "coincident with the Medieval Warm Period," which clearly exhibited greater warmth than was observed at any time during the Current Warm Period (see Figure 4.2.4.6.3.4).

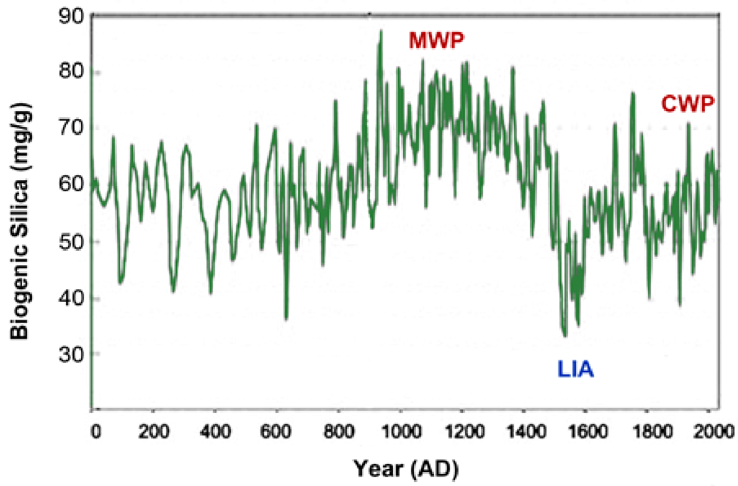

Figure 4.2.4.6.3.4. A 2,000-year record of climate variations reconstructed from Haukadalsvatn, West Iceland. Adapted from Geirsdottir, A., Miller, G.H., Thordarson, T., and Olafsdottir, K.B. 2009. A 2000-year record of climate variations reconstructed from Haukadalsvatn, West Iceland. *Journal of Paleolimnology* **41**: 95–115.

Giraudi (2009) examined "long-term relations among glacial activity, periglacial activity, soil development in northwestern Italy's alpine River Orco headwaters, and down-valley floods on the River Po," based on "studies carried out by means of geological and geomorphologic surveys on the glacial and periglacial features," including a sampling of soils involved in periglacial processes that "provided a basis for development of a chronological framework of late Holocene environmental change" and an analysis of "a stratigraphic sequence exposed in a peat bog along the Rio del Nel" about 1 km from the front edge of the Eastern Nel Glacier.

Giraudi determined between about 200 BC and AD 100—i.e., during the Roman Warm Period—"soils developed in areas at present devoid of vegetation and with permafrost," indicating temperatures at that time "probably reached higher values than those of the present." He also concludes, "analogous conditions likely occurred during the period of [the] 11th–12th centuries AD, when a soil developed on a slope presently characterized by periglacial debris," while noting "in the 11th–12th centuries AD, frost weathering processes were not active and, due to the higher temperatures than at present or the longer duration of a period with high temperatures, vegetation succeeded in colonizing the slope." He also found "the phase of greatest glacial expansion (Little Ice Age) coincides with a period characterized by a large number of floods in the River Po basin," and "phases of glacial retreat [such as occurred during the Roman and Medieval Warm Periods] correlate with periods with relatively few floods in the River Po basin."

Martin-Chivelet *et al.* (2011) developed a 4,000-year temperature history for the northern part of Castilla-Leon in northern Spain based on $\delta^{13}C$ data obtained from stalagmites recovered from three caves, each of which was situated approximately 50 km from a common central point (~42°40'N, 4°W), having found good correlation between the mean annual temperatures of the past 125 years (from a site located 14 km from one of the caves) and corresponding $\delta^{13}C$ data. According to the five researchers, their $\delta^{13}C$ record began with "an initial interval of broad warm conditions between 4000 and 3000 yr BP." Then came "a prolonged time during which thermal conditions become permanently cold," with the coldest conditions occurring between 2,850 and 2,550 yr BP, an interval they describe as "the 'first cold phase' of the Subatlantic period, also called in Europe the Iron Age Cold Period." Next came another warm period when "maximum temperatures were probably reached in the three hundred years interval between 2150 and 1750 yr BP," which corresponds, they write, "to the well-known Roman Warm Period, an interval which has been correlated with a phase of relatively high solar flux."

Thereafter came "another relatively cold episode, which lasted about 250 years and reached its minimum at ~1500 yr BP," which "correlated with the Dark Ages Cold Period described in other areas of Europe." Then, "a rapid trend of warming led to a new, prolonged interval of warmth" that lasted from 1,400 to 700 yr BP. Martin-Chivelet *et al.* state this Medieval Warm Period is "probably the most robust climatic feature in our records, perfectly outlined in the series of the three stalagmites." They also note, "the end of the Medieval Warm Period was marked by a progressive and rapid ... transition into the Little Ice Age, a relatively cold period broadly reported from all Europe and also from other areas in the world as far as South Africa or South America."

A graph of the researchers' data portrays the development of the Current Warm Period, and it suggests temperatures at the end of the twentieth century were about a quarter of a degree Centigrade warmer than the peak warmth of the Medieval Warm Period. They note studies in Northern Spain based on peat bog proxies "suggest that the temperatures during both the Roman Warm Period and the Medieval Warm Period were higher than present-day ones," citing Martinez-Cortizas *et al*. (1999).

Andrade *et al*. (2011) worked with a 2.5-m gravity core and an 18-cm box core taken from the outer area of the Ria de Muros (42°44'N, 9°02'W) on the northwestern coast of the Iberian Peninsula in June 2004 to establish a climate history of the region through "the combined use of textural analysis, magnetic properties and geochemical parameters (total concentrations of diagenetically stable and mobile elements in sediment and pore water)," which "allowed the identification of a current redox front and two palaeosedimentary redox fronts in the sediment record."

These three redox fronts, as the team of Spanish scientists describe them, "originated during periods of high marine/terrestrial organic matter ratio (as inferred from the ratio of total organic carbon to total nitrogen and $\delta^{13}C$)." They state, "sedimentation rates calculated from ^{14}C dating results identify these periods as known periods of increased upwelling and reduced continental input due to colder, drier climate in the NW Iberian Peninsula, namely the Little Ice Age, the Dark Ages, and the first cold period of the Upper Holocene." They also point out the lower proportion of oceanic influence observed between 1,250 and 560 cal. yr BP "coincides with the Medieval Warm Period, during which there was an increase in continental input to both the continental shelf (Mohamed *et al*., 2010) and the Rias of Vigo and Muros (Alvarez *et al*., 2005; Lebreiro *et al*., 2006)." FInally, they note the colder Dark Ages period was preceded by the "Roman Warm Period."

Morellon *et al*. (2011) write, "in the context of present-day global warming, there is increased interest in documenting climate variability during the last millennium," because "it is crucial to reconstruct pre-industrial conditions to discriminate anthropogenic components (i.e., greenhouse gases, land-use changes) from natural forcings (i.e., solar variability, volcanic emissions)." They conducted a multi-proxy study of several short sediment cores recovered from Lake Estanya (42°02'N, 0°32'E) in the Pre-Pyrenean Ranges of northeast Spain, which provide "a detailed record of the complex environmental, hydrological and anthropogenic interactions occurring in the area since medieval times." They report, "the integration of sedimentary facies, elemental and isotopic geochemistry, and biological proxies (diatoms, chironomids and pollen), together with a robust chronological control, provided by AMS radiocarbon dating and ^{210}Pb and ^{137}Cs radiometric techniques, enabled precise reconstruction of the main phases of environmental change, associated with the Medieval Warm Period (MWP), the Little Ice Age (LIA) and the industrial era."

The 13 researchers identified the MWP as occurring in their record from AD 1150 to 1300, noting their pollen data reflect "warmer and drier conditions," in harmony with the higher temperatures of the Iberian Peninsula over the same period that have been documented by Martinez-Cortizas *et al*. (1999), the higher temperatures of the Western Mediterranean region found by Taricco *et al*. (2008), and the global reconstructions of Crowley and Lowery (2000) and Osborn and Briffa (2006), all of which "clearly document warmer conditions from the twelfth to fourteenth centuries." This warmth, Morellon *et al*. state, is "likely related to increased solar irradiance (Bard *et al*., 2000), persistent La Niña-like tropical Pacific conditions, a warm phase of the Atlantic Multidecadal Oscillation, and a more frequent positive phase of the North Atlantic Oscillation (Seager *et al*., 2007)."

Following the MWP was the LIA, which Morellon *et al*. recognize as occurring from AD 1300 to 1850. Lower temperatures (Martinez-Cortizas *et al*., 1999) characterized this period on the Iberian Peninsula, which "coincided with colder North Atlantic (Bond *et al*., 2001) and Mediterranean sea surface temperatures (Taricco *et al*., 2008) and a phase of mountain glacier advance (Wanner *et al*., 2008)," they report. Following the LIA they identified the transition period of AD 1850–2004, which took the region into the Current Warm Period.

Morellon *et al*. write, "a comparison of the main hydrological transitions during the last 800 years in Lake Estanya and solar irradiance (Bard *et al*., 2000) reveals that lower lake levels dominated during periods of enhanced solar activity (MWP and post-1850 AD) and higher lake levels during periods of diminished solar activity (LIA)." Within the LIA, they note periods of higher lake levels or evidence of increased water balance occurred during the solar minima of Wolf (AD 1282–1342), Sporer (AD 1460–

1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1830).

In light of these observations, it appears the multi-centennial climate oscillation uncovered by the 13 researchers has been driven by a similar oscillation in solar activity and by multi-decadal solar activity fluctuations superimposed on that longer-period oscillation. These relationships suggest there is no compelling reason to attribute twentieth century global warming to the concomitant increase in the air's CO_2 content.

As noted in this section, a significant body of research documents the existence of the millennial-scale oscillation of climate that has alternately brought Earth both into and out of the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, and Little Ice Age, and, most recently, into the Current Warm Period. During these climatic transitions, except for the most recent one, there have been no significant changes in the atmosphere's CO_2 concentration, which suggests the transition out of the Little Ice Age and into the Current Warm Period likely had nothing at all to do with the concomitant increase in the air's CO_2 content.

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4.2.4.7 North America

As indicated in the introduction of Section 4.2.4, numerous peer-reviewed studies reveal modern temperatures are not unusual. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration. Conditions as warm as, or warmer than, the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 content remained at values approximately 30 percent lower than that of today.

The following subsections highlight evidence from North America, where much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, then the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; Current Warm Period is simply a manifestation of its latest phase. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

4.2.4.7.1 Alaska and Canada

Arseneault and Payette (1997) analyzed tree-ring and growth-form sequences obtained from more than 300 spruce remains buried in currently treeless peatland located near the tree line in northern Québec to produce a proxy record of climate for this region between AD 690 and 1591. Over this 900-year period, the trees of the region experienced several episodes of both suppressed and rapid growth, indicative of colder and warmer conditions, respectively, than those of the present, the scientists found. Cooler (suppressed growth) conditions prevailed in AD 760–860 and 1025–1400, and warmer (rapid growth) conditions were prevalent in AD 700–750, 860–1000, 1400–1450, and 1500–1570.

Further analysis of the warm period between AD 860 and 1000 led the two researchers to conclude the warmth experienced in northern Quebec during this period coincided with the Medieval Warm Period experienced across the North Atlantic and Northern Europe, which "exceeded in duration and magnitude both the 16th and 20th century warm periods identified previously [by other scientists] using the same methods." Furthermore, on the basis of current annual temperatures at their study site and the northernmost twentieth century location of the forest, which at that time was 130 km south of their site, they conclude, the "Medieval Warm Period was approximately 1°C warmer than the 20th century."

Campbell and Campbell (2000) analyzed pollen and charcoal records obtained from sediment cores retrieved from three small ponds—South Pond (AD 1655–1993), Birch Island Pond (AD 1499–1993), and Pen 5 Pond (400 BC–AD 1993)—located within Canada's Elk Island National Park, which covers close to 200 km^2 of the Beaver Hills region of east-central Alberta. Contrary to the intuitive assumption that there would be an "increase in fire activity with warmer and drier climate," the Canadian researchers found "declining groundwater levels during the Medieval Warm Period [MWP] allowed the replacement of substantial areas of shrub birch with the less fire-prone aspen, causing a decline in fire frequency and/or severity, while increasing carbon storage on the landscape." They conclude this scenario "is likely playing out again today," as all three of the sites they studied "show historic increases in *Populus* pollen and declines in charcoal."

The two researchers note Earth's present climate "is warmer and drier than that of either the Little Ice Age (which followed the MWP) or the early Neoglacial (preceding the MWP)," and we must therefore "consider the present pond levels to be more representative of the MWP than of the time before or after." But since their Pen 5 Pond data indicate sediment charcoal concentrations have not yet dropped to the level characteristic of the MWP—even with what they describe as the help of "active fire suppression in the park combined with what may be thought of as unintentional fire suppression due to agricultural activity around the park"—it appears their study sites and their surroundings have not yet risen to the level of warmth and dryness of the MWP, which they describe as having occurred over the period AD 800–1200.

Calkin *et al*. (2001) reviewed what they called "the most current and comprehensive research of Holocene glaciation" along the northernmost Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, noting several periods of glacial advance and retreat during the past 7,000 years. They describe a general retreat during the Medieval Warm Period that lasted for "at least a few centuries prior to AD 1200." After this Medieval Climatic Optimum, there were three major intervals of Little Ice Age glacial advance: the early fifteenth century, middle seventeenth century, and the last half of the nineteenth century. During these latter periods, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers "reached their Holocene maximum extensions."

The existence of a Medieval Warm Period and Little Ice Age in Alaska is an obvious reality. Glaciers there reached their maximum Holocene extensions during the Little Ice Age, and it can be inferred Alaskan temperatures reached their Holocene minimum during this period as well. It should therefore come as no surprise that temperatures in Alaska rose significantly above the chill of the Little Ice Age in the region's natural recovery from the coldest period of the Holocene.

Hu *et al*. (2001) "conducted multi-proxy geochemical analyses of a sediment core from Farewell Lake in the northwestern foothills of the Alaska Range," obtaining what they describe as "the first high-resolution quantitative record of Alaskan climate variations that spans the last two millennia." The team of five scientists report their results "suggest that at Farewell Lake SWT [surface water temperature] was as warm as the present at AD 0–300 [during the Roman Warm Period], after which it decreased steadily by ~3.5°C to reach a minimum at AD 600 [during the depths of the Dark Ages Cold Period]." From then, they state, "SWT increased by ~3.0°C during the period AD 600–850 and then [during the Medieval Warm Period] exhibited fluctuations of 0.5–1.0°C until AD 1200." Completing their narrative, they write, "between AD 1200–1700, SWT decreased gradually by 1.25°C [as the world descended into the depths of the Little Ice Age], and from AD 1700 to the present, SWT increased by 1.75C," the latter portion of which warming initiated the Current Warm Period.

Hu *et al*. remark, “the warmth before AD 300 at Farewell Lake coincides with a warm episode extensively documented in northern Europe … whereas the AD 600 cooling is coeval with the European ‘Dark Ages.’” They also report, “the relatively warm climate AD 850–1200 at Farewell Lake corresponds to the Medieval Climatic Anomaly, a time of marked climatic departure over much of the planet.” They note “these concurrent changes suggest large-scale teleconnections in natural climatic variability during the last two millennia, likely driven by atmospheric controls.”

Noting “20th-century climate is a major societal concern in the context of greenhouse warming,” Hu *et al*. conclude by reiterating their record “reveals three time intervals of comparable warmth: AD 0–300, 850–1200, and post-1800,” and they write, “these data agree with tree-ring evidence from Fennoscandia, indicating that the recent warmth is not atypical of the past 1000 years.”

These observations testify to the reality of the non-CO_2-induced millennial-scale oscillation of climate that brought the world, including Alaska, significant periods of warmth some 1,000 years ago, during the Medieval Warm Period, and some 1,000 years before that, during the Roman Warm Period. These earlier periods of warmth were unquestionably not caused by elevated atmospheric CO_2 concentrations, nor were they due to elevated concentrations of any other greenhouse gases. They were caused by something else, and the warmth of today could be due to that same cause.

Gedalof and Smith (2001) compiled a transect of six tree ring-width chronologies from stands of mountain hemlock growing near the treeline that extends from southern Oregon to the Kenai Peninsula, Alaska, analyzing the data in such a way as to “directly relate changes in radial growth to annual variations in the North Pacific ocean-atmosphere system.” Over the period of their study (AD 1599–1983), they determined “much of the pre-instrumental record in the Pacific Northwest region of North America [was] characterized by alternating regimes of relatively warmer and cooler SST [sea surface temperature] in the North Pacific, punctuated by abrupt shifts in the mean background state,” which were found to be “relatively common occurrences.” They found “regime shifts in the North Pacific have occurred 11 times since 1650.” Significantly, the abrupt 1976–1977 shift in this Pacific Decadal Oscillation, as it is generally called, was found to be responsible for the vast majority of the past half-century’s warming in Alaska.

Kaplan *et al*. (2002) reported on paleo-limnological inferences regarding Holocene climatic variability from a small lake in southern Greenland—Qipisarqo Lake (61°00’41”N, 47°45’13”W)—based on lake sediment physical-chemical properties, including magnetic susceptibility, density, water content, and biogenic silica and organic matter concentration. They found “the interval from 6000 to 3000 cal yr B.P. was marked by warmth and stability.” Thereafter, however, the climate cooled “until its culmination during the Little Ice Age.” From 1,300 to 900 cal yr B.P., there was a partial amelioration during the Medieval Warm Period, which was associated with an approximate 1.5°C rise in temperature. Then, after another brief warming between A.D. 1500 and 1750, the second and more severe portion of the Little Ice Age occurred, which in turn was followed by “naturally initiated post-Little Ice Age warming since A.D. 1850, which is recorded throughout the Arctic” and “has not yet reached peak Holocene warmth.”

The three researchers note “colonization around the northwestern North Atlantic occurred during peak Medieval Warm Period conditions that ended in southern Greenland by AD 1100.” Norse movements around the region thereafter occurred at what they describe as “perhaps the worst time in the last 10,000 years, in terms of the overall stability of the environment for sustained plant and animal husbandry.” The demise of the Norse colonies clearly was the result of “the most environmentally unstable period since deglaciation.” They conclude, “current warming, however rapid, has not yet reached peak Holocene warmth.”

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Alberta’s Pine Lake (52°N, 113.5°W) to provide a non-vegetation-based high-resolution record of climate variability for this part of North America over the past 4,000 years. This effort revealed periods of both increasing and decreasing grain size (moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales, with the most predominant departures including four several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500–1900), Medieval Warm Period (about AD 700–1300), Dark Ages Cold Period (about 100 BC to AD 700), and Roman Warm Period (about 900–100 BC). A standardized median grain-size history indicated the highest rates of stream discharge during the past 4,000 years occurred during the Little Ice Age at approximately 300–350 years ago, when grain sizes were about 2.5 standard deviations above the 4,000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2 standard deviations below the 4,000-year mean. Most recently, grain size over the past 150 years has generally remained above average.

The Pine Lake sediment record thus convincingly identifies the non-CO_2-induced millennial-scale climate oscillation that brings several-century-long periods of alternating dryness and wetness to the southern Alberta region of North America, during concomitant periods of relative hemispheric warmth and coolness, respectively. It also demonstrates there is nothing unusual about the region's current moisture status, which suggests the planet may still have a bit of warming to do before the Current Warm Period is fully upon us.

Laird *et al*. (2003) studied diatom assemblages in sediment cores taken from three Canadian and three United States lakes situated within the northern prairies of North America. For five of the lakes, diatom-inferred salinity estimates were used to reconstruct relative changes in effective moisture (E/P), where E is evaporation and P is precipitation, with high salinity implying high E/P. For the sixth lake, diatom-inferred total phosphorus was used, and chronologies were based on ^{210}Pb dating of recent sediments and radiocarbon dates for older sediments.

The seven scientists note their data show "shifts in drought conditions on decadal through multicentennial scales have prevailed in this region for at least the last two millennia." In Canada, major shifts occurred near the beginning of the Medieval Warm Period, and in the United States they occurred near its end. The scientists state, "distinct patterns of abrupt change in the Northern Hemisphere are common at or near the termination of the Medieval Warm Period (*ca*. A.D. 800–1300) and the onset of the Little Ice Age (*ca*. A.D. 1300–1850)." They also note "millennial-scale shifts over at least the past 5,500 years, between sustained periods of wetter and drier conditions, occurring approximately every 1,220 years, have been reported from western Canada (Cumming *et al*., 2002)," and "the striking correspondence of these shifts to large changes in fire frequencies, inferred from two sites several hundreds of kilometers to the southwest in the mountain hemlock zone of southern British Columbia (Hallett *et al*., 2003), suggests that these millennial-scale dynamics are linked and operate over wide spatial scales."

Lassen *et al*. (2004) point out "the Norse, under Eric the Red, were able to colonize South Greenland at AD 985, according to the Icelandic Sagas, owing to the mild Medieval Warm Period climate with favorable open-ocean conditions." They also mention the arrival of the Norsemen was "close to the peak of Medieval warming recorded in the GISP2 ice core which was dated at AD 975 (Stuiver *et al*., 1995)," and Esper *et al*. (2002) independently identified the peak warmth of this period throughout North American extratropical latitudes as "occurring around 990." It would appear the window of climatic opportunity provided by the peak warmth of the Medieval Warm Period was a major factor enabling seafaring Scandinavians to establish stable settlements on the coast of Greenland.

As time progressed, however, the glowing promise of the apex of Medieval warmth gave way to the debilitating reality of the depth of Little Ice Age cold. Jensen *et al*. (2004), for example, report the diatom record of Igaliku Fjord "yields evidence of a relatively moist and warm climate at the beginning of settlement, which was crucial for Norse land use," but "a regime of more extreme climatic fluctuations began soon after AD 1000, and after AD c. 1350 cooling became more severe." Lassen *et al*. additionally note, "historical documents on Iceland report the presence of the Norse in South Greenland for the last time in AD 1408," during what they describe as a period of "unprecedented influx of (ice-loaded) East Greenland Current water masses into the innermost parts of Igaliku Fjord." They also report "studies of a Canadian high-Arctic ice core and nearby geothermal data (Koerner and Fisher, 1990) correspondingly showed a significant temperature lowering at AD 1350–1400," when, they write, "the Norse society in Greenland was declining and reaching its final stage probably before the end of the fifteenth century."

Many more details of this incredible saga of five centuries of Nordic survival at the foot of the Greenland Ice Cap also have come to light. Based on a high-resolution record of the fjord's subsurface water-mass properties derived from analyses of benthic foraminifera, Lassen *et al*. conclude stratification of the water column, with Atlantic water masses in its lower reaches, appears to have prevailed throughout the last 3,200 years, except for the Medieval Warm Period. During that period, which they describe as occurring between AD 885 and 1235, the outer part of Igaliku Fjord experienced enhanced vertical mixing (which they attribute to increased wind stress) that would have been expected to increase nutrient availability there. A similar conclusion was reached by Roncaglia and Kuijpers (2004), who found evidence of increased bottom-water ventilation between AD 960 and 1285.

Based on these findings, plus evidence of the presence of *Melonis barleeanus* during the Medieval Warm Period (the distribution of which is mainly controlled by the presence of partly decomposed organic matter), Lassen *et al*. conclude surface productivity in the fjord during this interval of unusual relative warmth was "high and thus could have provided a good supply of marine food for the Norse people."

Shortly thereafter, the cooling that led to the Little Ice Age was accompanied by a gradual re-stratification of the water column, which curtailed nutrient upwelling and the high level of marine productivity that had prevailed throughout the Medieval Warm Period. These linked events, according to Lassen *et al*., "contributed to the loss of the Norse settlement in Greenland." With deteriorating growing conditions on land and simultaneous reductions in oceanic productivity, it was only a matter of time before the Nordic colonies failed. Lassen *et al*. note, "around AD 1450, the climate further deteriorated with further increasing stratification of the water-column associated with stronger advection of (ice-loaded) East Greenland Current water masses." This led to an even greater "increase of the ice season and a decrease of primary production and marine food supply," which "could also have had a dramatic influence on the local seal population and thus the feeding basis for the Norse population."

Lassen *et al*. conclude "climatic and hydrographic changes in the area of the Eastern Settlement were significant in the crucial period when the Norse disappeared." Also, Jensen *et al*. report, "geomorphological studies in Northeast Greenland have shown evidence of increased winter wind speed, particularly in the period between AD 1420 and 1580 (Christiansen, 1998)," noting "this climatic deterioration coincides with reports of increased sea-ice conditions that caused difficulties in using the old sailing routes from Iceland westbound and further southward along the east coast of Greenland, forcing sailing on more southerly routes when going to Greenland (Seaver, 1996)."

Jensen *et al*. conclude, "life conditions certainly became harsher during the 500 years of Norse colonization," and this severe cooling-induced environmental deterioration "may very likely have hastened the disappearance of the culture." It is also clear the more favorable living conditions associated with the peak warmth of the Medieval Warm Period—which occurred between approximately AD 975 (Stuiver *et al*., 1995) and AD 990 (Esper *et al*., 2002)—were what originally enabled the Norse to colonize the region. In the thousand-plus subsequent years, there has never been a sustained period of comparable warmth, nor of comparable terrestrial or marine productivity, either locally or hemispherically (and likely globally, as well).

D'Arrigo *et al*. (2004) sampled trees of white spruce (*Picea glauca* (Moench) Voss) from 14 sites near the elevational treeline on the eastern Seward Peninsula of Alaska, obtaining 46 cores from 38 trees, which they used to develop a maximum latewood density (MXD) chronology for the period AD 1389 to 2001. Calibrating a portion of the latter part of this record (1909–1950) against May–August monthly temperatures obtained from the Nome meteorological station, they converted the entire MXD chronology to warm-season temperatures. This process revealed, they write, "the middle-20th century warming is the warmest 20-year interval since 1640." Their plot of reconstructed temperatures, however, clearly shows a nearly equivalent warm period near the end of the 1600s, as well as a two-decade period of close-to-similar warmth in the mid-1500s. In the latter part of the 1400s there is a decade warmer than that of the mid-twentieth century. This temperature reconstruction, which the five researchers described as "one of the longest density-based records for northern latitudes," thus provides yet another indication twentieth century warmth was by no means unprecedented in the past millennium or two, contrary to the claims of Mann *et al*. (1998, 1999) and Mann and Jones (2003). The study instead supports the findings of Esper *et al*. (2002, 2003), McIntyre and McKitrick (2003), and Loehle (2004), which indicate there were several periods over the past millennium or more when it was as warm as, or even warmer than, it was during the twentieth century.

Luckman and Wilson (2005) used new tree-ring data from the Columbia Icefield area of the Canadian Rockies to present a significant update to a millennial temperature reconstruction published for this region in 1997. The update employed different standardization techniques, such as the regional curve standardization method, to capture a greater degree of low frequency variability (centennial to millennial scale) than reported in the initial study. In addition, the new dataset added more than one hundred years to the chronology that now covers the period 950–1994.

The new tree-ring record was found to explain 53 percent of May–August maximum temperature variation observed in the 1895–1994 data and was thus viewed as a proxy indicator of such temperatures over the past millennium. Based on this relationship, the record showed considerable decadal- and centennial-scale variability, where generally warmer conditions prevailed during the eleventh and twelfth centuries, between about 1350–1450, and from about 1875 through the end of the record. The warmest reconstructed summer occurred in 1434 and was 0.23°C warmer than the next warmest summer, which occurred in 1967, and persistent cold conditions prevailed in 1200–1350, 1450–1550, and 1650–1850, with the 1690s being exceptionally cold (more than 0.4°C colder than other intervals).

The revised Columbia Icefield temperature reconstruction provides further evidence for natural climate fluctuations on centennial-to-millennial time scales and, according to Luckman and Wilson, "appears to indicate a reasonable response of local trees to large-scale forcing of climates, with reconstructed cool conditions comparing well with periods of known low solar activity."

D'Arrigo *et al*. (2005) used a new tree-ring width dataset derived from 14 white spruce chronologies obtained from the Seward Peninsula, Alaska, covering the years 1358–2001, combined with additional tree-ring width chronologies from northwest Alaska, to produce two versions of a much longer data series that extended to AD 978. The first chronology was created using traditional methods of standardization (STD), which do not perform well in capturing multidecadal or longer climate cycles, while the second chronology utilized the regional curve standardization (RCS) method, which better preserves low-frequency variations at multidecadal time scales and longer. The new, improved, and extended final temperature history of this study provided further evidence for natural climate fluctuations on centennial-to-millennial time scales, capturing the temperature oscillations that produced the Medieval Warm Period (eleventh–thirteenth centuries) and Little Ice Age (1500–1700).

Hallett and Hills (2006) reconstructed the Holocene environmental history of Kootenay Valley in the southern Canadian Rockies based on data obtained from the sediments of Dog Lake, British Columbia (50°46'N, 116°06'W). They found in the centuries leading up to AD 800, the area had developed "a more open landscape," and "fire frequencies and summer drought appear to increase," concluding this increased fire activity was "supported by higher dry-open/wet-closed [forest] pollen ratios and indicates a return to dry-open forest conditions around Dog Lake," which lasted about 400 years. Thereafter, they found, "wet-closed forest cover reaches its maximum extent from 700–150 cal years BP [AD 1250–1800]" in what "appears to be a response to Little Ice Age cooling." Finally, they state, "current global warming trends ... may again create the conditions necessary for dry-open ... forest to expand in the Kootenay Valley." The authors say current global warming may recreate climatic conditions similar to those that prevailed in the Kootenay Valley prior to the global chill of the Little Ice Age, which suggests it has not been as warm there yet, nor for as long a time, as it was between AD 800 and 1200.

Loso *et al*. (2006) presented "a varve thickness chronology from glacier-dammed Iceberg Lake [60°46'N, 142°57'W] in the southern Alaska icefields," where "radiogenic evidence confirms that laminations are annual and record continuous sediment deposition from AD 442 to AD 1998" and where "varve thickness increases in warm summers because of higher melt, runoff, and sediment transport." They report the temperatures implied by the varve chronology "were lowest around AD 600, warm between AD 1000 and AD 1300 [which they called "a clear manifestation of the Medieval Warm Period"], cooler between AD 1500 and AD 1850, and have increased dramatically since then."

The four scientists state their varve record "suggests that 20th century warming is more intense ... than the Medieval Warm Period or any other time in the last 1500 years."Their graphical representation of varve thickness suggests the intense warming of the twentieth century peaked around 1965 to 1970, after which it was followed by equally intense cooling, such that by 1998, temperatures are implied to have been less than they were during the Medieval Warm Period. The same story is told by tree ring-width anomalies from the adjacent Wrangell Mountains of Alaska, which Loso *et al*. portray as updated from Davi *et al*. (2003). These two databases show the region's current temperature is lower than it was during the warmest part of the Medieval Warm Period.

Hay *et al*. (2007) analyzed the vertical distributions of diatoms, silicoflagellates, and biogenic silica found in two sediment cores recovered from the inner and outer basins (49°04’N, 125°09’W and 49°02’N, 125°09’W, respectively) of Effingham Inlet, British Columbia, Canada, finding evidence that “a period of warmer and drier climate conditions and possibly increased coastal upwelling offshore occurred ca. 1450–1050 calendar years before present”; i.e., about AD 500–900. Noting “the patterns observed in the diatom record of Effingham Inlet are consistent with regional marine and terrestrial paleoenvironmental records,” they report, “coast range glaciers ... showed a hiatus from 1500 to 1100 calendar years before present,” and this “period of more productive conditions ... was correlative with increased regional primary and marine fish production.” In addition, their data indicated concentrations of *Skeletonema costatum*, which they say “is limited by low temperatures,” were much greater over the AD 550–950 period (which appears to represent the Medieval Warm Period in this part of the world) than in any portion of the following (most recent) millennium.

Zabenskie and Gajewski (2007) extracted sediment cores from Lake JR01 (69°54’N, 95°4.2’W) on the Boothia Peninsula, Nunavut, Canada using a 5-cm diameter Livinstone corer. They note “the uppermost part of the sediment was sampled in a plastic tube with piston to ensure that the sediment-water interface was collected,” and “the upper 20 cm of sediment were sub-sampled into plastic bags at 0.5-cm intervals.” From the fossil pollen assemblages thereby derived, July temperatures were estimated “using the modern analog technique,” as per Sawada (2006). As illustrated in Figure 4.2.4.7.1.1, the two researchers report “maximum estimated July temperatures were reached between 5800 and 3000 cal yr BP, at which time they exceeded present-day values.” Thereafter, temperatures decreased, but with a subsequent “short warming,” which they say “could be interpreted as the Medieval Warm Period,” which they identify as occurring “between 900 and 750 cal yr BP.” After that period of warmth, “temperatures cooled during the Little Ice Age,” as pollen percentages “returned to their values before the [MWP] warming.” During the last 150 years of the record, they observe a “diverse and productive diatom flora,” although “July temperatures reconstructed using the modern analog technique remained stable during this time,” which suggests the Lake JR01 region of the Boothia Peninsula is currently not as warm as it was during the MWP.

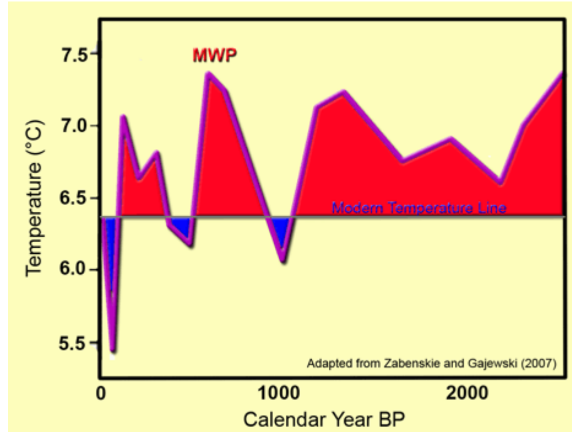

Figure 4.2.4.7.1.1. Reconstructed July mean temperature on the Boothia Peninsula, Nunavut, Canada. Adapted from Zabenskie, S. and Gajewski, K. 2007. Post-glacial climatic change on Boothia Peninsula, Nunavut, Canada. *Quaternary Research* **68**: 261–270.

Podritske and Gajewski (2007) evaluated the relationship between diatoms and temperature by comparing a diatom stratigraphy based on high-resolution sampling with independent paleoclimatic records. They used a high-resolution diatom sequence of the past 9,900 years developed from sediment-core data acquired from a small lake (unofficially named KR02) on Canada’s Victoria Island (located at 71.34°N, 113.78°W) to place recent climatic changes there “in an historical context.” The two researchers report “there is evidence of diatom community response to centennial-scale variations such as the ‘Medieval Warm Period’ (~1000–700 cal yr BP), ‘Little Ice Age’ (~800–150 cal yr BP) and recent warming.” They report the recent warming-induced changes “are not exceptional when placed in the context of diatom community changes over the entire Holocene,” stating, “although recent changes in diatom community composition, productivity, and species richness are apparent, they were surpassed at other periods throughout the Holocene.” The researchers explicitly state the most recent rate of change “was exceeded during the Medieval Warm Period.”

Wiles *et al*. (2008) used “comparisons of temperature sensitive climate proxy records with tree-ring, lichen and radiocarbon dated histories from land-terminating, non-surging glaciers for the last two millennia from southern Alaska” to “identify summer temperature as a primary driver of glacial expansions,” based on “field and laboratory work over the past decade" that yielded "five new or updated glacier histories," one each for Bear Glacier (Kenai Mountains), Marathon Mountain Cirque (Kenai Mountains), Amherst Glacier (Chugach Mountains), Crescent Glacier (Chugach Mountains), and Yakutat Glacier (St. Elias Mountains), all located just above the Gulf of Alaska (about 60°N) between approximately 140 to 150°W.

The four researchers' findings suggest the presence of the Roman Warm Period near the beginning of their 2,000-year record, because of detected "general glacier expansions during the First Millennium AD" that experienced their "strongest advance" at AD 600. The latter cold interval—with ice extent "as extensive as [the] subsequent Little Ice Age"—is typically known as the Dark Ages Cold Period. This cold interval was followed by the Medieval Warm Period (MWP), the evidence for which consisted of "soil formation and forest growth on many forefields in areas that today are only just emerging from beneath retreating termini," which suggests the MWP was likely both warmer and longer-lived than what has been experienced so far in the Current Warm Period. They also report, "tree-ring chronologies [at the Sheridan, Tebenkof, and Princeton glaciers] show that forest growth on these forefields was continuous between the 900s and 1200s."

Noting the alternating warm-cold-warm-cold-warm sequence of the past 2,000 years "is consistent with millennial-scale records of ice-rafted debris flux in the North Atlantic and Northern Hemisphere temperature reconstructions," and "variable Holocene solar irradiance has been proposed as a potential forcing mechanism for millennial-scale climate change," they conclude "this is supported by the Southern Alaskan glacial record."

Besonen *et al*. (2008) derived thousand-year histories of varve thickness and sedimentation accumulation rate for Canada's Lower Murray Lake (81°20'N, 69°30'W), which is typically covered for about 11 months of each year by ice that reaches a thickness of 1.5 to 2 meters at the end of each winter. They note, "field-work on other High Arctic lakes clearly indicates sediment transport and varve thickness are related to temperatures during the short summer season that prevails in this region, and we have no reason to think that this is not the case for Lower Murray Lake." The six scientists report the varve thickness and sediment accumulation rate histories of Lower Murray Lake show "the twelfth and thirteenth centuries were relatively warm." Their data indicate Lower Murray Lake and its environs were often much warmer during this time period (AD 1080–1320) than at any point in the twentieth century, which also has been shown to be the case for Donard Lake (66.25°N, 62°W) by Moore *et al*. (2001).

Payette *et al*. (2008) developed a long-term, spatially explicit fire history of northern boreal forest-tundra in the Riviere Boniface watershed in northeastern Canada (57°45'N, 76°W) based on several years of field investigations designed to exhaustively map and accurately date the occurrences of all fires per each 100-year interval over the last 2,000 years within a 40-km^2 area in that region. They found there was a "70% reduction of forest cover since 1800 yr BP and nearly complete cessation of forest regeneration since 900 yr BP," such that "the northern part of the forest tundra in Eastern Canada has been heavily deforested over the last millennium." They also note "the climate at the tree line was drier and warmer before 900 cal. yr BP."

The three Canadian researchers conclude the chief direct cause of the post-900 yr BP deforestation was "climate deterioration coinciding with the phasing-out of the Medieval Warmth and incidence of the Little Ice Age." In addition, since "the latitudinal position of successful post-fire regeneration of lichen-spruce woodlands is situated approximately 1.5° south of the Boniface area, as a rule of thumb it is probable that a drop of at least 1°C in mean annual temperature occurred after 900 cal. yr BP," they conclude. "Recovery of the boreal forest after a long period of deforestation will require sustained warming," they state, which they add has been occurring only "since the mid-1990s in Eastern subarctic Canada."

Edwards *et al*. (2008) developed a cellulose $\delta^{13}C$ dendrochronology "from cross-dated 10-year increments of 16 sub-fossil snags and living-tree ring sequences of *Picea engelmannii* (Englemann spruce) from upper alpine treeline sites near Athabasca Glacier and subfossil material from the forefield of Robson Glacier plus living and snag material of *Pinus albicaulis* (whitebark pine) adjacent to Bennington Glacier, spanning AD 951–1990," as well as from an oxygen isotope ($\delta^{18}O$) dendro-chronology for the same period. They calculated past changes in relative humidity and temperature over Canada's Columbia Icefield in the general vicinity of 53°N, 118°W. They report several "intriguing new discoveries," one of which is "evidence of previously unrecognized winter warmth during the Medieval Climate Anomaly (~AD 11001250)," as illustrated in Figure 4.2.4.7.1.2.

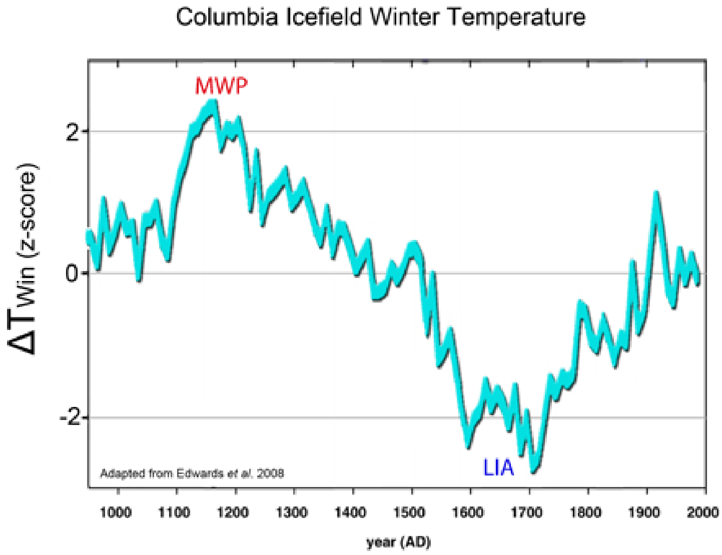

Figure 4.2.4.7.1.2. Columbia Icefield mean winter temperature z-scores relative to that of the period AD 1941-1990. Adapted from Edwards, T.W.D., Birks, S.J., Luckman, B.H., and MacDonald, G.M. 2008. Climatic and hydrologic variability during the past millennium in the eastern Rocky Mountains and northern Great Plains of western Canada. *Quaternary Research* **70**: 188–197.

The four researchers' results show the peak winter temperature of the Medieval Climate Anomaly throughout Canada's Columbia Icefield was warmer than the peak temperature of the Current Warm Period (which appears to have occurred ~1915), and it was even warmer than the mean temperature of the 1941–1990 base period as well as the mean temperature of the last ten years of that period (1980–1990).

Barclay *et al*. (2009) note "tree-ring crossdates of glacially killed logs have provided a precisely dated and detailed picture of Little Ice Age (LIA) glacier fluctuations in southern Alaska," and they extended this history into the First Millennium AD (FMA) by integrating similar data obtained from additional log collections made in 1999 with the prior data to produce a new history of advances and retreats of the Tebenkof Glacier spanning the past two millennia.

Figure 4.2.4.7.1.3 shows between the FMA and LIA extensions of the Tebenkof Glacier terminus, there was a period between about AD 950 and 1230 when the terminus dropped further than two kilometers back from the maximum LIA extension that occurred near the end of the nineteenth century. This warmer/drier period of glacier terminus retreat had to have been much more extreme than what was experienced at any time during the twentieth century, because at the century's end the glacier's terminus had not yet retreated more than two kilometers back from the line of its maximum LIA extension. This 280-year period of likely greater warmth and dryness falls in the middle of the broad peak of maximum warmth during the global Medieval Warm Period.

Based on the data depicted in Figure 4.2.4.7.1.3, it would appear the central portion of the Medieval Warm Period in southern Alaska was likely significantly warmer and drier than at any time during the twentieth century. It can be further concluded there is nothing unprecedented or unusual about that region's current warmth and dryness, which means there is no need to invoke anthropogenic CO_2 emissions as a cause.

Rolland *et al*. (2009) reconstructed the late-Holocene evolution of a Southampton Island lake known as Tasiq Qikitalik (65°05'70'N, 83°47'49'W)

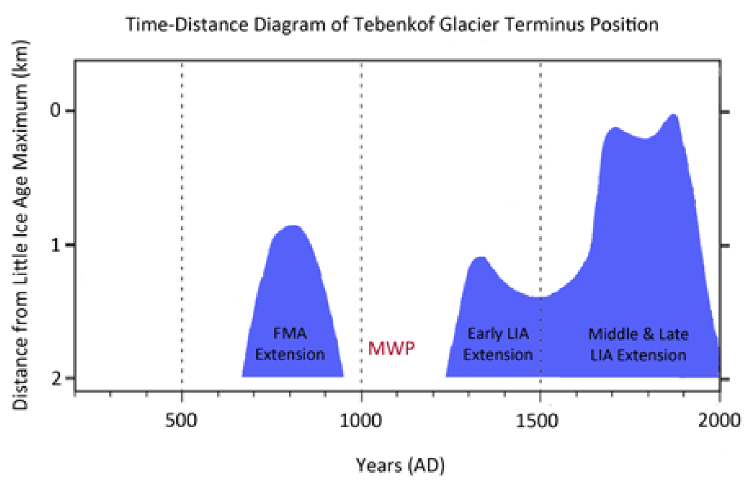

Figure 4.2.4.7.1.3. The temporal history of the distance by which the terminus of the Tebenkof Glacier fell short of its maximum LIA extension over the past two millennia. Adapted from Barclay, D.J., Wiles, G.C., and Calkin, P.E. 2009. Tree-ring crossdates for a first millennium AD advance of Tebenkof Glacier, southern Alaska. *Quaternary Research* **71**: 22–26.

in Nunavut, Canada by studying fossil chironomid distributions along with sedimentological data (X-ray fluorescence, grain size, and C/N ratios) obtained from a sediment core retrieved from the lake's deepest reachable point, deriving in the process a 1,200-year history of inferred August temperatures. They discovered "higher temperatures were recorded from cal yr AD 1160 to AD 1360, which may correspond to the Medieval Warm Period," and "between cal yr AD 1360 and AD 1700, lower temperatures were probably related to a Little Ice Age event," with the latter period exhibiting a minimum August temperature "ca. 2°C colder than the maximum observed during the Medieval Warm Period." The most recent August temperature, which occurred at the end of the record at about 2008, is approximately 0.9°C less than the maximum August temperature of the Medieval Warm Period.

Laird and Cumming (2009) developed a history of changes in the level of Lake 259 (Rawson Lake, 49°40'N, 93°44'W) within the Experimental Lakes Area of northwestern Ontario, Canada based on a suite of near-shore gravity cores they analyzed for diatom species identity and concentration, as well as organic matter content. They discovered "a distinct decline in lake level of ~2.5 to 3.0 m from ~800 to 1130 AD." This interval, they write, "corresponds to an epic drought recorded in many regions of North America from ~800 to 1400 AD," which they say was "often referred to as the Medieval Climatic Anomaly or the Medieval Warm Period," and which also "encompasses 'The Great Drought' of the thirteenth century (Woodhouse and Overpeck, 1998; Woodhouse, 2004; Herweijer *et al*. 2007)." They note the Canadian prairies were at that time "experiencing reductions in surface-water availability due to climate warming and human withdrawals (Schindler and Donahue, 2006)," and many regions in the western U.S. had experienced water supply deficits in reservoir storage with the multi-year drought described by Cook *et al*. (2007). They report "these severe multi-year drought conditions pale in comparison to the many widespread megadroughts that persisted for decades and sometimes centuries in many parts of North America over the last millennium (Woodhouse, 2004)."

Clegg *et al*. (2010) conducted a high-resolution analysis of midge assemblages found in the sediments of Moose Lake (61°22.45'N, 143°35.93'W) in the Wrangell-St. Elias National Park and Preserve of south-central Alaska, based on data obtained from cores removed from the lake bottom in summer 2000 and a midge-to-temperature transfer function that yielded mean July temperatures (T_{July}) for the past six thousand years. Some of the results of this study are portrayed in Figure 4.2.4.7.1.4, which shows, from about 2,600 cal yr BP to the present, a clear multi-centennial oscillation about the declining trend, with peaks and valleys defining the temporal locations of the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and the start of the Current Warm Period, which is still not expressed to any significant degree compared to the Medieval and Roman Warm Periods.

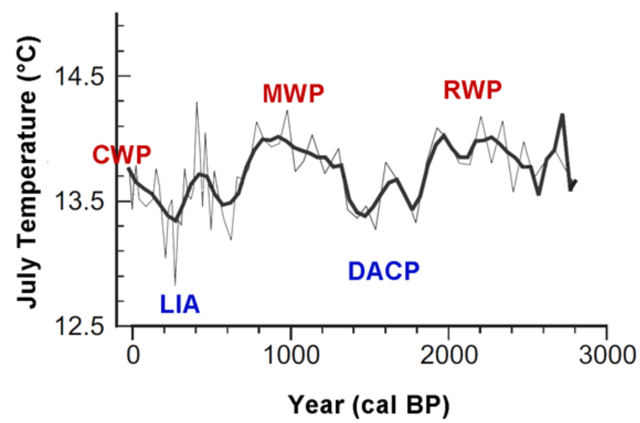

Figure 4.2.4.7.1.4. Mean July near-surface temperature (°C) vs. years before present (cal BP) for south-central Alaska (USA). Adapted from Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tinner, W., and Hu, F.S. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. *Quaternary Science Reviews* **29**: 3308–3316.

The seven scientists write, "comparisons of the T_{July} record from Moose Lake with other Alaskan temperature records suggest that the regional coherency observed in instrumental temperature records (e.g., Wiles *et al*., 1998; Gedalof and Smith, 2001; Wilson *et al*., 2007) extends broadly to at least 2000 cal BP." In addition, they note climatic events such as the LIA and the MWP occurred "largely synchronously" between their T_{July} record from Moose Lake and a $\delta^{18}O$-based temperature record from Farewell Lake on the northwestern foothills of the Alaska Range, and "local temperature minima likely associated with First Millennium AD Cooling (centered at 1400 cal BP; Wiles *et al*., 2008) are evident at both Farewell and Hallet lakes (McKay *et al*., 2008)."

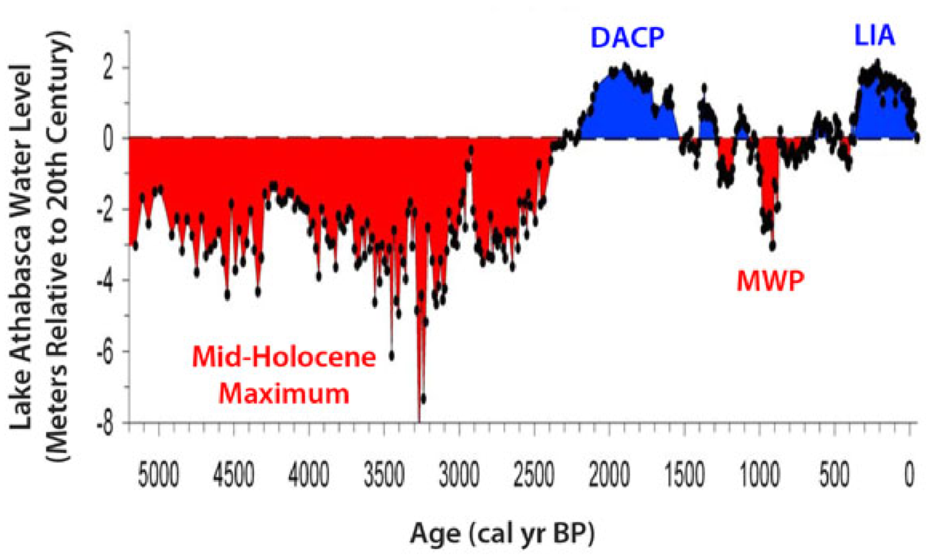

Figure 4.2.4.7.1.5. The Reconstructed water level history of Lake Athabasca. Adapted from Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/ 2011GL047599.

Wolfe *et al*. (2011) note the level of Canada's Lake Athabasca—North America's ninth-largest lake, located in the northwest corner of Saskatchewan and the northeast corner of Alberta between 58° and 60° N—"is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains (Wolfe *et al*., 2008; Johnston *et al*., 2010; Sinnatamby *et al*., 2010)." In addition, they write, "paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks (Wolfe *et al*., 2008)." They also note "the highest levels of the last 1000 years occurred c. 1600–1900 CE [=AD] during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies," and the "lowest levels existed at c. 970–1080 CE at a time of low glacier volume," near the midpoint of the global Medieval Warm Period.

In their newest study of the subject, the four Canadian researchers expanded the time span of the lake-level history to the past 5,200 years, based on new analyses of sediment cores they collected in July 2004 from North Pond (a lagoon on Bustard Island located at the western end of Lake Athabasca). They discovered (see Figure 4.2.4.7.1.5) "modern society in western Canada developed during a rare interval of relatively abundant freshwater supply—now a rapidly diminishing by-product of the LIA glacier expansion, which is in agreement with late 20th century decline in Athabasca River discharge identified in hydrometric records (Burn *et al*., 2004; Schindler and Donahue, 2006)." In addition, their data suggest "the transition from water abundance to scarcity can occur within a human lifespan," which, as they caution, "is a very short amount of time for societies to adapt."

Their data suggest the peak warmth of the Medieval Warm Period was likely significantly greater than the peak warmth experienced to date during the Current Warm Period. The rapidly declining water level over the past couple of decades—when Earth's temperature was near its modern peak but exhibited very little trend—suggests lake level could continue its rapid downward course if planetary temperatures merely maintain their current values. Wolfe *et al*. conclude, "as consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory."

Galloway *et al*. (2011) studied an 11.6-m sediment core they extracted in June 2001 from the deepest point of Felker Lake (51°57.0'N, 121°59.9'W), which sits in the rain shadow generated by Canada's Coast, Cascade, and Columbia Mountains. They analyzed diatom assemblages, together with pollen and spore types and quantities, to produce an 11,670-year record of hydrological change throughout the Holocene, based on a calibration dataset of 219 lakes from British Columbia, including Felker Lake, and select lakes from the Northern Great Plains (Wilson *et al*., 1996). This work provided evidence for what they call a "millennial-scale pacing of climate" throughout the Holocene. They report "the most extreme episode of hydrological change occurred from ca. 1030 cal. year BP to ca. 690 cal. year BP," a period they note was "broadly coeval with the Medieval Warm Period." They say "a coeval warm and dry interval is recognized in numerous paleoclimate studies in western North America," citing the work of Hallett *et al*. (2003), Laird *et al*. (2003), and Bracht *et al*. (2007).

That the warm and dry interval Galloway *et al*. discovered at Felker Lake during the heart of the Medieval Warm Period was the most extreme such period of the entire Holocene indicates just how unusual the Medieval Warm Period was in this regard … and further reveals the *non*-uniqueness of the warmth and dryness experienced in that part of the world during the establishment of the planet's Current Warm Period.

Kobashi *et al*. (2011) write, "Greenland recently incurred record high temperatures and ice loss by melting, adding to concerns that anthropogenic warming is impacting the Greenland ice sheet and in turn accelerating global sea-level rise." They also note "it remains imprecisely known for Greenland how much warming is caused by increasing atmospheric greenhouse gases versus natural variability." They reconstructed Greenland surface snow temperature variability over the past 4,000 years at the GISP2 site (near the Summit of the Greenland ice sheet; hereafter referred to as Greenland temperature) with a new method that utilizes argon and nitrogen isotopic ratios from occluded air bubbles, as described in detail by Kobashi *et al*. (2008a,b).

The eight researchers report "the temperature record starts with a colder period in 'the Bronze Age Cold Epoch,'" which they say was followed by "a warm period in 'the Bronze Age Optimum,'" after which there was a 1,000-year cooling that began "during 'the Iron/Roman Age Optimum,'" followed by "the Dark Ages." That period was followed by "the Medieval Warm Period," after which occurred "the Little Ice Age, which they describe as "the coldest period of the past 4000 years," which was followed, finally, by "the recent warming." They note "the current decadal average surface temperature at the summit is as warm as in the 1930s–1940s, and there was another similarly warm period in the 1140s (Medieval Warm Period)," indicating "the present decade is not outside the envelope of variability of the last 1000 years." They write, "excluding the last millennium," there were fully "72 decades warmer than the present one, in which mean temperatures were 1.0 to 1.5°C warmer," and during two centennial intervals, average temperatures "were nearly 1.0°C warmer than the present decade" (see Figure 4.2.4.7.1.6).

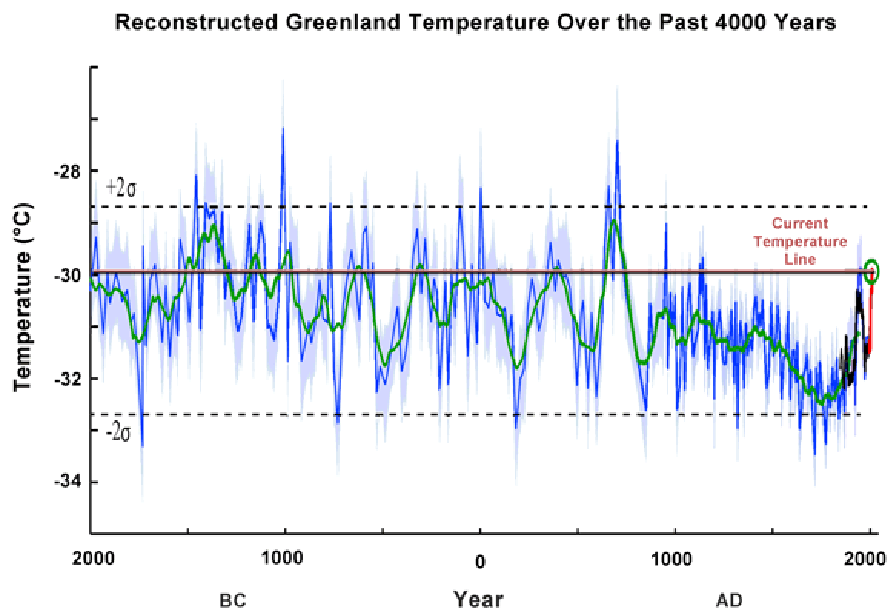

Figure 4.2.4.7.1.6. Reconstructed Greenland snow surface temperatures for the past 4,000 years. The blue line and blue band represent the reconstructed Greenland temperature and 1σ error, respectively. The green line represents a 100-year moving average of the blue line. The black and red lines indicate the Summit and AWS decadal average temperatures, respectively, as calculated by others. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: 10.1029/2011GL049444.

Since the Greenland summit's decadal warmth of the first ten years of the twenty-first century was exceeded fully six dozen times over the prior four millennia, it clearly was in no way unusual, and therefore it is also clear none of Greenland's recent warming has necessarily been caused by increasing concentrations of greenhouse gases. It is far more likely its recent warmth is the next expected phase of the natural oscillation of climate that has produced numerous multi-century periods of alternating warmth and cold over the past four thousand years.

Bunbury and Gajewski (2012) obtained sediment cores from two lakes in the interior southwest of Canada's Yukon Territory—Jenny Lake (61.04°N, 138.36°W) and Upper Fly Lake (61.04°N, 138.09°W)—which, they write, "yielded chironomid records that were used to provide quantitative estimates of mean July air temperature." The two researchers report their chironomid-inferred temperature estimates from the two lakes "compare well with one another and also with other paleoclimate evidence from the region," noting their data suggest "relatively warm conditions during medieval times, centered on AD 1200, followed by a cool Little Ice Age, and warming temperatures over the past 100 years." It can be estimated from the graphical representations of their data that the Medieval Warm Period at both lake sites extended from about AD 1100 to 1350, and it also can be estimated that the most recent (AD 1990) of their temperature determinations were about 0.8°C cooler than the peak warmth of the Medieval Warm Period at Jenny Lake and approximately 0.5°C cooler at Upper Fly Lake.

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4.2.4.7.2 United States

The IPCC claims rising atmospheric CO_2 concentrations due to the burning of fossil fuels such as coal, gasm and oil have raised global air temperatures to their highest level in the past one to two millennia. Therefore, investigating the possibility of a period of equal global warmth within the past one to two thousand years has become a high-priority enterprise, for if such a period can be shown to have existed when the atmosphere's CO_2 concentration was far less than it is today, there will be no compelling reason to attribute the warmth of our day to the CO_2 released into the air by mankind since the beginning of the Industrial Revolution. This section reviews studies of this topic conducted within the confines of the lower 48 contiguous states of the United States of America.

Lloyd and Graumlich (1997) derived 3,500-year histories of treeline elevation fluctuation and tree abundance for five sites in the southern Sierra Nevada (~36.5°N, 108.25°W). They found synchronous increases in treeline elevation from AD 800 to 900 and an episode of high tree abundance above the current treeline between AD 700 and 1200, which implies warmer-than-present temperatures during that period..

Ingram *et al*. (1998) conducted isotopic ($^{18}O/^{16}O$ and $^{13}C/^{12}C$) and elemental chemical analyses (Sr/Ca and Mg/Ca ratios) of sediment cores taken from Petaluma Marsh, San Francisco Bay, Northern California, to develop a record of paleoenvironmental change in this region over the past 700 years. They report high frequency variations in $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, and Sr/Ca were noted throughout the 700-yr record, indicating the presence of oscillations in freshwater inflow, temperature, and evaporation at periods of 35–115 years. Between 150 and 400 cal yr BP, $\delta^{18}O$ and Mg/Ca were relatively low, indicating a period of cold and wet climatic conditions associated with the Little Ice Age. Before that, $\delta^{18}O$ and Mg/Ca were higher from 480 to 650 cal yr BP, indicating, in the words of Ingram *et al*., "drier and warmer conditions during the end of the Medieval Warm Period." In addition, they note, the record "suggests that the duration of wet and dry periods was greater over the past 700 years than in the twentieth century instrumental record." Ingram *et al*.'s work supports the findings of Graumlich (1990), who found tree-ring evidence in the nearby Sierra Nevada Mountains that the period from 510 to 420 cal yr BP was warmer and wetter than any part of the twentieth century.

Patterson (1998) obtained seasonal temperature variations from $\delta^{18}O(CaCO_3)$ values of late Holocene sagittal fish otoliths recovered from archaeological sites along the southern and western basin of Lake Erie (~41.5°N, 82.75°W). At the turn of the first millennium AD, "both summer maximum and mean annual temperatures in the Great Lakes region were found to be higher than those of the 20th century," whereas winter temperatures at that time were lower, Patterson writes. Summer temperatures at AD 985 were 2 to 6°C warmer than those of 1936–1992, and mean annual temperatures were 0.2°C higher and mean winter temperatures 1.8°C lower. Hence, there was probably no significant difference between the mean annual temperature around AD 985 and the mean annual temperature of the 1980s and 1990s.

Hadley *et al*. (1998) examined body size characteristics of pocket gopher (*Thomomys talpoides*) remains obtained from Lamar Cave, Yellowstone National Park (~45°N, 110°W). During the Medieval Warm Period, pocket gophers had a significantly shorter (89 percent of mean value) diastema (the gap between the animals' molars and incisors) and presumably smaller body size than in colder times, the scientists found. This finding, they write, "accords with Bergmann's rule, which states that animals from warmer parts of a geographic range tend to be smaller." Because modern diastema lengths are not nearly as short as diastema lengths during Medieval times (see Figure 4.2.4.7.2.1), it can be concluded the MWP was likely warmer than the CWP.

Gavin and Brubaker (1999) extracted three 18-cm-deep soil cores from three sites within a subalpine meadow they refer to as Meadow Ridge in Royal Basin (47°49'N, 123°12'30" W), a north-facing glacial valley at the headwaters of Royal Creek in

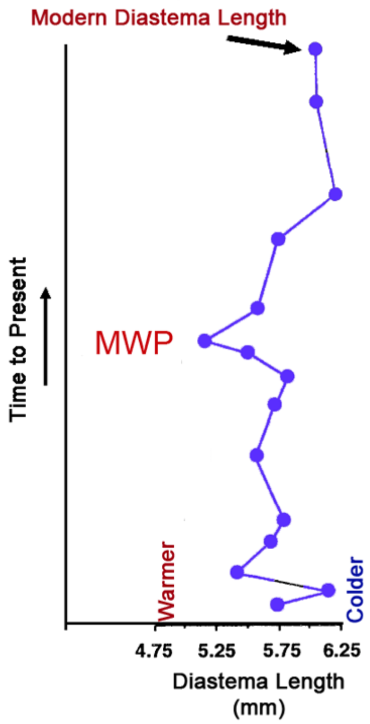

Figure 4.2.4.7.2.1. Diasteme length of pocket gopher remains obtained from Lamar Cave, Yellowstone National Park. Adapted from Hadley, E.A., Kohn, M.H., Leonard, J.A., and Wayne, R.K. 1998. A genetic record of population isolation in pocket gophers during Holocene climatic change. *Proceedings of the National Academy of Sciences, USA* **95**: 6893–6896..

northeastern Olympic National Park in the state of Washington. They constructed depth (= time) profiles of pollen types and abundances over the past six millennia. Based on current associations of the plants that produced the pollen with various climatic parameters, primarily temperature and precipitation, they reconstructed a climatic history of the three sites.

In the part of the soil profiles "corresponding to the Medieval Warm Period (c. 1200–700 BP)," all sites showed an increase in the abundance of *Polygonum bistortoides*, "an indicator of mesic conditions." At one of the sites, it reached a maximum abundance of 50 percent, which they say is "more than three times the value in any modern surface sample at Meadow Ridge." In addition, one of the sites showed "a decline in Cyperaceae (cf. *Carex nigricans*)," which "suggests earlier snow-melt dates." They conclude the observed changes "suggest long and moist growing seasons" during the Medieval Warm Period. In addition, they note the pollen-plant relationship they developed for *P. bistortoides* over this period "corresponds to c. 75% cover," which is "higher than any reported *Polygonum bistortoides* cover in the Olympic Mountains (Schreiner, 1994)," suggesting the MWP of AD 800–1300 was very likely significantly warmer than the Current Warm Period in that part of the world has been to date.

Field and Baumgartner (2000) developed "a robust time series of stable isotope [$\delta^{18}O$ from *Neogloboquadrina dutertrei*] variability over the past millennium from the varved sediments of the Santa Barbara Basin," which they related to observed environmental variability within this part of the California Current over the past half-century, thereby demonstrating "thermal variability dominates the $\delta^{18}O$ signal."

The two researchers report, "an anomalously warm coastal ocean persisted at the multicentennial-scale from roughly AD 1200 to 1450," and this period, as they describe it, "coincides with the age generally assigned to the 'Medieval Warm Period.'" They also report "the period of positive anomalies in the low-frequency series of $\delta^{18}O$ from *N. dutertrei* that continues from ~AD 1450 to ~1800 is consistent with the dates associated with the cooling and neoglaciation of the 'Little Ice Age' in both the Southern and Northern Hemispheres." In addition, they note "the long-term ocean warming and cooling of the California Current region appears to be in phase with the warming and cooling of the midlatitude North Atlantic described by Keigwin (1996)."

Brush (2001) analyzed sediment cores obtained from tributaries, marshes, and the main stem of Chesapeake Bay for paleoecological indicators of regional climate change and land-use variations over the past millennium. They found "the Medieval Climatic Anomaly and the Little Ice Age are recorded in Chesapeake sediments by terrestrial indicators of dry conditions for 200 years, beginning about 1000 years ago, followed by increases in wet indicators from about 800 to 400 years ago." This MCA is what most people refer to as the Medieval Warm Period (MWP), which Brush says is "recognized in many parts of the world from historical and paleocological evidence." The findings of this paper therefore represent additional evidence for the uniqueness of both the Medieval Warm Period and the Little Ice Age, the two preeminent climatic anomalies of the past thousand years, further suggesting there is nothing unusual about the global warming of the past century or so, as it represents the planet's natural recovery from the global chill of the Little Ice Age and the start of its return to conditions more like those of the Medieval Warm Period.

Viau *et al*. (2002) analyzed a set of 3,076 ^{14}C dates from the North American Pollen Database used to date sequences in more than 700 pollen diagrams across North America. They found nine millennial-scale oscillations during the past 14,000 years in which continent-wide synchronous vegetation changes with a periodicity of roughly 1,650 years were recorded in the pollen records. The most recent of the vegetation transitions was centered at approximately 600 years BP (before present). This event, they write, culminated "in the Little Ice Age, with maximum cooling 300 years ago." Before that event, a major transition that began approximately 1,600 years BP represents the climatic amelioration that culminated "in the maximum warming of the Medieval Warm Period 1000 years ago," they note. And so it goes, back through the Holocene and into the preceding late glacial period, with the times of all major pollen transitions being "consistent with ice and marine records."

According to the five researchers, "the large-scale nature of these transitions and the fact that they are found in different proxies confirms the hypothesis that Holocene and late glacial climate variations of millennial-scale were abrupt transitions between climatic regimes as the atmosphere-ocean system reorganized in response to some forcing." They go on to state, "although several mechanisms for such natural forcing have been advanced, recent evidence points to a potential solar forcing (Bond *et al*., 2001) associated with ocean-atmosphere feedbacks acting as global teleconnections agents." In addition, they note, "these transitions are identifiable across North America and presumably the world."

Willard *et al*. (2003) examined the late Holocene (2,300 yr BP to present) record of Chesapeake Bay, along with the adjacent terrestrial ecosystem in its watershed, through the study of fossil dinoflagellate cysts and pollen derived from sediment cores. They report "several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records."

The first of these periods of lower-than-average precipitation, which spanned the period 200 BC–AD 300, occurred during the latter part of the Roman Warm Period, as delineated by McDermott *et al*. (2001) on the basis of a high-resolution speleothem $\delta^{18}O$ record from southwest Ireland. The next such period (~AD 800–1200), in the words of the three researchers, "corresponds to the 'Medieval Warm Period,' which has been documented as drier than average by tree-ring (Stahle and Cleaveland, 1994) and pollen (Willard *et al*., 2001) records from the southeastern USA." Other periods consisting of several decadal-scale dry intervals spanned the years AD 1320–1400 and AD 1525–1650.

The researchers also state, "mid-Atlantic dry periods generally correspond to central and southwestern USA 'megadroughts,' described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity." In addition, "droughts in the late sixteenth century that lasted several decades, and those in the 'Medieval Warm Period' and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al*., 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al*., 2000; Laird *et al*., 1996a, 1996b) and detrital clastic records (Dean, 1997)."

The work of Willard *et al*. (2003) demonstrates the reality of the millennial-scale hydrologic cycle that accompanies the millennial-scale temperature cycle responsible for producing alternating warm and cold intervals such as the Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and Current Warm Period. It also confirms the global warming of the twentieth century has not yet produced unusually strong wet and dry periods, contradicting claims that warming will exacerbate extreme climate anomalies.

Cook *et al*. (2004) developed a 1,200-year history of drought for the western half of the United States and adjacent parts of Canada and Mexico (hereafter the "West"), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66 percent of them) possessed reconstructions that extended back to AD 800. This reconstruction revealed "some remarkable earlier increases in aridity that dwarf the comparatively short-duration current drought in the 'West.'" Also of great interest, "the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occurred during a ~400 year interval of overall elevated aridity from AD 900 to 1300," which they say was "broadly consistent with the Medieval Warm Period."

The five scientists write, "the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests anomalously warm climate conditions during that time may have contributed to the development of more frequent and persistent droughts in the 'West.'" After citing nine other studies that provide independent evidence of significant drought during this time period for various sub-regions of the "West," they warn, "any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America." If the association between warmth and drought in the "West" is robust, as their data suggest, temperatures of the latter part of the twentieth century and the first part of the twenty-first century must still be significantly less than those experienced during large segments of the Medieval Warm Period over much of western North America and the United States in particular.

Carbotte *et al*. (2004) located fossil oyster beds within the Tappan Zee area of the Hudson River estuary (New York, USA) via chirp sub-bottom and side-scan sonar surveys and retrieved sediment cores from the sites that provided shells for radiocarbon dating. The researchers found "oysters flourished during the mid-Holocene warm period," when "summertime temperatures were 2–4°C warmer than today (e.g., Webb *et al*., 1993; Ganopolski *et al*., 1998)." Thereafter, they note, the oysters "disappeared with the onset of cooler climate at 4,000–5,000 cal. years BP," but they "returned during warmer conditions of the late Holocene," which the authors specifically identify as the Roman and Medieval Warm Periods as delineated by Keigwin (1996) and McDermott *et al*. (2001). The authors state, "these warmer periods coincide with the return of oysters in the Tappan Zee." They also report their shell dates suggest a final "major demise at ~500–900 years BP," which they describe as being "consistent with the onset of the Little Ice Age," noting further that in nearby Chesapeake Bay, "Cronin *et al*. (2003) report a sustained period of cooler springtime water temperatures (by ~2–5°C) during the Little Ice Age relative to the earlier Medieval Warm Period." Carbotte *et al.* add, "similar aged fluctuations in oyster presence are observed within shell middens elsewhere along the Atlantic seaboard," citing results obtained from Maine to Florida.

This study of the periodic establishment and demise of oyster beds in the Hudson River estuary and elsewhere along the east coast of the United States paints a clear picture of alternating, multi-century warm and cold intervals over the past two millennia that is vastly different from the 1,000-year-long "hockey stick" temperature history of Mann *et al*. (1998, 1999) and the 2,000-year-long history produced by Mann and Jones (2003), in which Northern Hemispheric and global mean temperatures show essentially no low-frequency variability until the advent of the twentieth century, when temperatures are portrayed as rising dramatically, allowing to the authors to incorrectly claim twentieth century warming was driven by anthropogenic CO_2 emissions.

Sridhar *et al*. (2006) studied the orientation, morphology, and internal structure of dunes in the easternmost (wettest) portion of the Nebraska Sand Hills, where shallow core and outcrop samples indicate the dunes were formed 800 to 1,000 years ago when aridity was widespread and persistent across western North America. In addition, based on wind data obtained from six meteorological stations in and near the Nebraska Sand Hills, they employed a computer program to calculate the sand-drift vectors of dunes that would form today if the sand were free to move and not held in place by prairie grass. They found the current configuration of the Sand Hill dunes could not have been created by the region's current wind regime, in which air currents from the south in the spring and summer bring moist air from the Gulf of Mexico to the U.S. Great Plains. Instead, their work indicates the spring and summer winds that formed the dunes 800 to 1,000 years ago must have come from the southwest, bringing much drier and hotter-than-current air from the deserts of Mexico, with greatly reduced opportunities for rain.

This work clearly suggests much of western North America was likely both drier and hotter during the Medieval Warm Period, 800 to 1,000 years ago, than it is today. As Sridhar *et al*. note, "the dunes record a historically unprecedented large-scale shift of circulation that removed the source of moisture from the region during the growing season." They suggest the resultant drier and warmer conditions may have been further "enhanced and prolonged," as they phrase it, "by reduced soil moisture and related surface-heating effects," which effects are not operative in our day to the degree they were 800 to 1,000 years ago, as was demonstrated by still other of Sridhar *et al*.'s computer analyses.

Rasmussen *et al*. (2006), who had previously demonstrated "speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004)," concentrated on two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1) in the Guadalupe Mountains. Both records suggest periods of dramatic precipitation variability over the last 3,000 years, exhibiting large shifts unlike anything seen in the modern record. They also discovered the period from AD 900–1300 "includes severe drought events, consistent with tree-ring data for the western U.S. (Cook *et al*., 2004)," but the preceding and following centuries (AD 100–750 and AD 1500–1800) "show increased precipitation variability ... coinciding with increased El Niño flooding events."

These findings suggest moisture extremes much greater than those observed in the modern era are neither unusual nor manmade; they are simply a normal part of Earth's natural climatic variability. In addition, Rasmussen *et al*.'s data clearly reveal the occurrence of the Medieval Warm Period, as well as the Dark Ages Cold Period that preceded it and the Little Ice Age that followed it, in terms of available moisture, for in this part of the world, global warmth is typically manifest in terms of low available moisture and global coolness is typically manifest in terms of high available moisture.

Millar *et al*. (2006) studied dead tree trunks located above the current treeline on the tephra-covered slopes of Whitewing Mountain and San Joaquin Ridge south of Mono Lake just east of the Inyo Craters in the eastern Sierra Nevada range of California (USA), identifying the species to which the tree remains belonged, dating them, and (using contemporary distributions of the species in relation to contemporary temperature and precipitation) reconstructing paleoclimate during the time they grew there. They report, "the range of dates for the deadwood samples, AD 815–1350, coincides with the period identified from multiple proxies in the Sierra Nevada and western Great Basin as the Medieval Climate Anomaly," among which were tree-ring reconstructions indicating "increased temperature relative to present (Graumlich, 1993; Scuderi, 1993) and higher treelines (Graumlich and Lloyd, 1996; Lloyd and Graumlich, 1997), and pollen reconstructions [that] show greater abundance of fir in high-elevation communities than at present (Anderson, 1990)."

The five researchers also note "the Medieval forest on Whitewing was growing under mild, favorable conditions (warm with adequate moisture)," as indicated by "extremely low mean sensitivities [to stress] and large average ring widths." They conclude, as reported in their paper's abstract, annual minimum temperatures during the Medieval Climatic Anomaly in the region they studied were "significantly warmer" (+3.2°C) "than present." They say their results "closely compare to climate projections for California in AD 2070–2099 (Hayhoe *et al*., 2004)," in which "average temperature increases of 2.3–5.8°C were projected."

Malamud-Roam *et al*. (2006) conducted an extensive review of "the variety of paleoclimatic resources for the San Francisco Bay and watershed in order to identify major climate variations in the pre-industrial past, and to compare the records from the larger watershed region with the Bay records in order to determine the linkages between climate experienced over the larger watershed region and conditions in the San Francisco Bay." This work revealed "intermittent mega-droughts of the Medieval Climate Anomaly (ca. AD 900–1350) coincided with a period of anomalously warm coastal ocean temperatures in the California Current," and "oxygen isotope compositions of mussel shells from archaeological sites along the central coast also indicate that sea surface temperatures were slightly warmer than present." In contrast, they note, "the Little Ice Age (ca. AD 1450–1800) brought unusually cool and wet conditions to much of the watershed," and "notably stable conditions have prevailed over the instrumental period, i.e., after ca. AD 1850, even including the severe, short-term anomalies experienced during this period," namely, "the severe droughts of the 1930s and the mid-1970s." In this part of the world, therefore, peak Medieval warmth appears to have exceeded peak modern warmth. Also, as the four researchers note, when longer paleoclimate records are considered, "current drought conditions experienced in the US Southwest do not appear out of the range of natural variability."

Benson *et al*. (2007) review and discuss possible impacts of early-eleventh, middle-twelfth, and late-thirteenth century droughts on three Native American cultures that occupied parts of the western United States (Anasazi, Fremont, Lovelock) plus another culture that occupied parts of southwestern Illinois (Cahokia). They found "population declines among the various Native American cultures were documented to have occurred either in the early-11th, middle-12th, or late-13th centuries"—AD 990–1060, 1135–1170, and 1276–1297, respectively—and "really extensive droughts impacted the regions occupied by these prehistoric Native Americans during one or more of these three time periods." In particular, they say the middle-twelfth century drought "had the strongest impact on the Anasazi and

Mississippian Cahokia cultures," noting "by AD 1150, the Anasazi had abandoned 85% of their great houses in the Four Corners region and most of their village sites, and the Cahokians had abandoned one or more of their agricultural support centers, including the large Richland farming complex." In addition, they write, "the sedentary Fremont appear to have abandoned many of their southern area habitation sites in the greater Unita Basin area by AD 1150 as well as the eastern Great Basin and the Southern Colorado Plateau," so "in some sense, the 13th century drought may simply have 'finished off' some cultures that were already in decline." The researchers say these "major reductions in prehistoric Native American habitation sites/population" occurred during a period of "anomalously warm" climate conditions, which characterized the Medieval Warm Period throughout much of the world at that particular time.

Graham *et al*. (2007) conducted an extensive review of Medieval Warm Period–Little Ice Age climatic conditions as revealed in a variety of proxy records obtained throughout western North America. The great balance of this evidence pointed to "generally arid conditions across much of the western and central US from as early as 400 A.D. until about 1300 A.D., followed by a rapid shift towards a wetter regime resembling modern climate." The heart of this Medieval Climate Anomaly (MCA) "lasted from about 800–1250 A.D. and included episodes of severe centennial-scale drought," which "affected regions stretching from northern Mexico, California and central Oregon, eastward through the Great Basin and into the western prairies of the central US." The 11 researchers state, "medieval times witnessed a distinctive pattern of climate change in many regions around the planet," and "as such, the findings suggest the evolution of the concept of an Atlantic-European 'Medieval Warm Period' into a surprisingly sharp instance of Holocene climate change with near-global manifestations." Or as they rephrase it in the final paragraph of their paper, "the near-global scale of MCA climate change seems to be becoming more apparent."

Stahle *et al*. (2007) used "an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook *et al*., 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America." During the Current Warm Period to date, "the Dust Bowl drought of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America," the authors found, citing the studies of Worster (1979), Diaz (1983), and Fye *et al*. (2003). During the Little Ice Age, they found three megadroughts, which they defined as "very large-scale drought[s] more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle *et al*., 2000)." They also note, "much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine, 1994; Laird *et al*., 2003; Cook *et al*., 2004)." These megadroughts were so phenomenal the authors refer to them as "no-analog Medieval megadroughts."

Climate models typically project that CO_2-induced global warming will result in more severe droughts. The much more severe and sustained megadroughts of the Little Ice Age appear to render such projections somewhat dubious. On the other hand, the still more severe and sustained no-analog megadroughts of the Medieval Warm Period would appear to bolster their projections. But the incredibly more severe droughts of that earlier period—if they were indeed related to high global air temperatures—would suggest it is not nearly as warm currently as it was during the Medieval Warm Period, when there was much less CO_2 in the air than there is today. These observations undercut the more fundamental claim that the historical rise in the air's CO_2 content has been responsible for unprecedented twentieth century global warming that has taken Earth's mean air temperature to a level unprecedented over the past two millennia.

Carson *et al*. (2007) developed a Holocene history of flood magnitudes in the northern Uinta Mountains of northeastern Utah from reconstructed cross-sectional areas of abandoned channels and relationships relating channel cross-sections to flood magnitudes derived from modern stream guage and channel records. They found over the past 5,000 years the record of bankfull discharge "corresponds well with independent paleoclimate data for the Uinta Mountains," and "during this period, the magnitude of the modal flood is smaller than modern during warm dry intervals and greater than modern during cool wet intervals." They note "the decrease in flood magnitudes following 1000 cal yr B.P. corresponds to numerous local and regional records of warming during the Medieval Climatic Anomaly."

The three researchers' graphical results, as shown in Figure 4.2.4.7.2.2, suggest the three largest negative departures from modern bankfull flood magnitudes (indicating greater than modern warmth) ranged from approximately 15 percent to 22 percent, as best as can be determined from visual inspection of their plotted data. These departures occurred between about 750 and 600 cal yr B.P., as determined from radiocarbon dating of basal channel-fill sediments. In addition to showing the degree of natural variability in northeastern Utah flood magnitudes throughout the Holocene has been much larger (in both positive and negative directions) than what has been observed in modern times, Carson *et al.*'s findings confirm the portion of the Medieval Warm Period between about AD 1250 and 1400 was likely significantly warmer than current conditions.

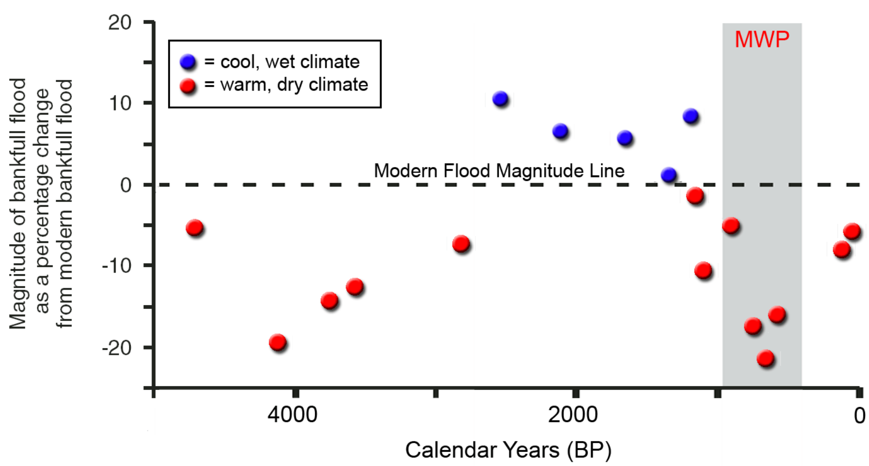

Figure 4.2.4.7.2.2. Uinta Mountains reconstructed climatic history derived from paleoflood chronology. Adapted from Carson, E.C., Knox, J.C., and Mickelson, D.M. 2007. Response of bankfull flood magnitudes to Holocene climate change, Uinta Mountains, northeastern Utah. *Geological Society of America Bulletin* **119**: 1066–1078.

Richey *et al*. (2007) note the variability of the hemispheric temperature reconstructions of Mann and Jones (2003) over the past one to two thousand years are "subdued (≤ 0.5°C)," and their low-amplitude reconstructions are not compatible "with several individual marine records that indicate that centennial-scale sea surface temperature (SST) oscillations of 2–3°C occurred during the past 1–2 k.y. (i.e., Keigwin, 1996; Watanabe *et al*., 2001; Lund and Curry, 2006; Newton *et al*., 2006)," just as they also differ from "tree-ring and multi-proxy reconstructions designed to capture multi-centennial-scale variability (e.g., Esper *et al*., 2002; Moberg *et al*., 2005)." This suggests "the amplitude of natural climate variability over the past 1 k.y. is >0.5°C," they write.

Richey *et al*. then explain how "a continuous decadal-scale resolution record of climate variability over the past 1400 years in the northern Gulf of Mexico was constructed from a box core recovered in the Pigmy Basin, northern Gulf of Mexico [27°11.61'N, 91°24.54'W]," based on climate proxies derived from "paired analyses of Mg/Ca and $\delta^{18}O$ in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages." The four researchers report, "two multi-decadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm as, or warmer than, near-modern conditions between 1000 and 1400 yr B.P.," and "foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was 2–2.5°C below modern SST" (Figure 4.2.4.7.2.3). In addition, they found "four minima in the Mg/Ca record between 900 and 250 yr. B.P. correspond with the Maunder, Sporer, Wolf, and Oort sunspot minima."

MacDonald *et al*. (2008) define the term "perfect drought" as "a prolonged drought that affects southern California, the Sacramento River basin and the upper Colorado River basin simultaneously," noting the instrumental record indicates the occurrence of such droughts throughout the past century but that they "generally persist for less than five years." That they have occurred at all, however, suggests the possibility of even longer "perfect droughts," that could prove catastrophic for the region. The three researchers explored the likelihood of such droughts occurring in the years to come, based on dendrochronological reconstructions of the winter Palmer Drought Severity Index (PDSI)

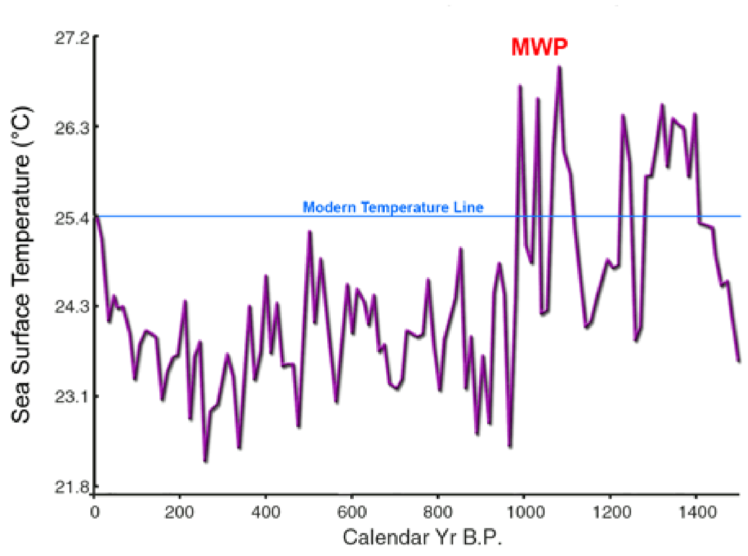

Figure 4.2.4.7.2.3. Annual Mg/Ca-derived SST anomalies for Pigmy Basin, Northern Gulf of Mexico. Adapted from Richey, J.N., Poore, R.Z., Flower, B.P., and Quinn, T.M. 2007. 1400 yr multiproxy record of climate variability from the northern Gulf of Mexico. *Geology* **35**: 423–426.

in southern California over the past thousand years (Figure 4.2.4.7.2.4) and the concomitant annual discharges of the Sacramento and Colorado Rivers (Figure 4.2.4.7.2.5), under the logical assumption that what has occurred before may happen again.

MacDonald *et al*. report finding "prolonged perfect droughts (~30–60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th century during the period of the so-called 'Medieval Climate Anomaly,'" This leads them to conclude, "prolonged perfect droughts due to natural or anthropogenic changes in radiative forcing, are a clear possibility for the near future."

Another conclusion that can be drawn from MacDonald *et al*.'s findings is that the current warmth of the world is not yet as great as it was during the peak heat of the Medieval Warm Period, or we might have already experienced, or currently be in the process of experiencing, a multidecadal perfect drought. That such has not occurred is encouraging, but it must be remembered that even if the theory of CO_2-induced global warming is incorrect or vastly overstated, further natural warming could push the planet's climate over the "tipping point" that initiates such a drought. That Earth has experienced no net warming over the past decade or so is a good sign in this regard, but there is no guarantee the globe will not begin to warm again, at any time and for whatever reason. Planning for the possibility of a significant perfect drought would appear to be warranted.

McGann (2008) analyzed a sediment core retrieved from the western portion of south bay near San Francisco International Airport (37°37.83'N, 122°21.99'W) for the presence of various foraminifers as well as oxygen and carbon stable isotopes and numerous trace elements found in tests of *Elphidium excavatum*. The U.S. Geological Survey researcher states, "benthic foraminiferal abundances, stable carbon and oxygen isotopes, and Mg/Ca ratios suggest that the climate of south bay has oscillated numerous times between warm and dry, and cool and wet conditions over the past 3870 years." "Both the Medieval Warm Period [MWP] and the Little Ice Age [LIA] are evident," she notes. She identifies the MWP as occurring from AD 743 to 1343 and the LIA as occurring in two stages: AD 1450 to 1530 and AD 1720 to 1850. She states, the timing of the MWP "correlates well with records obtained for Chesapeake Bay (Cronin *et al*., 2003), Long Island Sound (Thomas *et al*., 2001; Varekamp *et al*., 2002), California's Sierra Nevada (Stine, 1994), coastal northernmost California (Barron *et al*., 2004), and in the San Francisco Bay estuary in north bay at Rush Ranch (Byrne *et al*., 2001) and south bay at Oyster Point (Ingram *et al*., 1996)," She notes the cooler and wetter conditions of the LIA have been reported "in Chesapeake Bay (Cronin *et al*., 2003), Long Island Sound (Thomas *et al*., 2001; Varekamp *et al*., 2002), coastal northernmost California (Barron *et al*., 2004), and in the San Francisco Bay estuary at Rush Ranch (Bryne *et al*., 2001), Petaluma Marsh (Ingram *et al*., 1998), and in Richardson Bay (Ingram and DePaolo, 1993)." McGann also notes, "near the top of the core" foraminiferal abundances suggest, "once again, regional warming has taken place." That warming does not appear to have returned the region to the level of sustained warmth it enjoyed during the peak warmth of the MWP.

Analyzing isotopic soil carbon measurements made on 24 modern soils and 30 buried soils scattered between latitudes 48 and 32°N and longitudes 106 and 98°W, Nordt *et al*. (2008) developed a time series of C_4 vs. C_3 plant dynamics for the past 12 ka (ka =

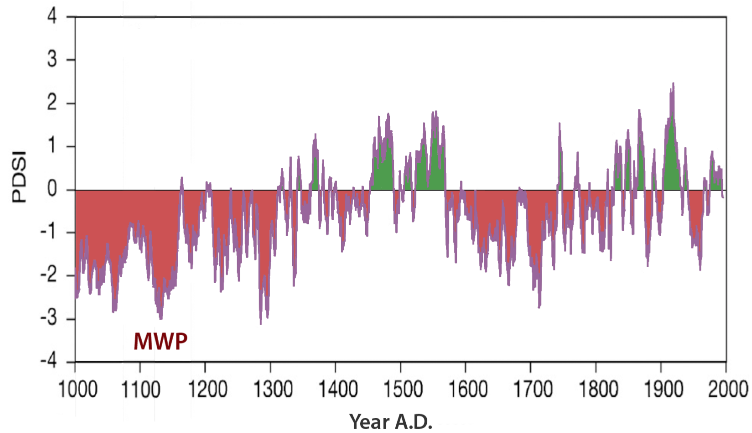

Figure 4.2.4.7.2.4. Reconstructed winter PSDI for Southern California since AD 1100. Adapted from MacDonald, G.M., Kremenetski, K.V., and Hidalgo, H.G. 2008. Southern California and the perfect drought: Simultaneous prolonged drought in Southern California and the Sacramento and Colorado River systems. *Quaternary International* **188**: 11–23.

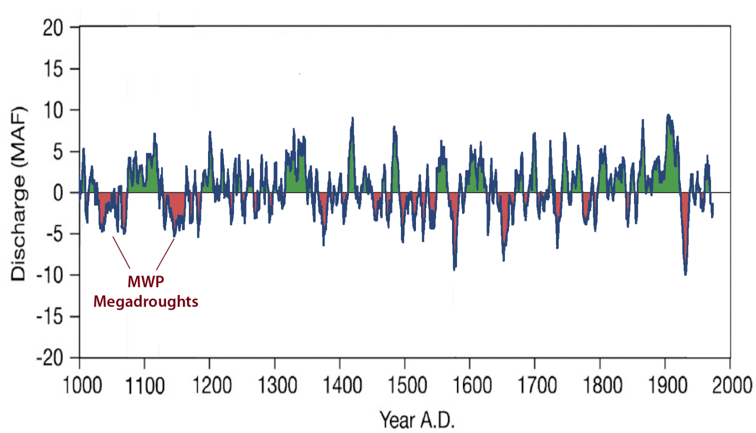

Figure 4.2.4.7.2.5. Five-year moving average of combined annual discharge deviations for the Sacramento and Colorado Rivers since AD 1100. Adapted from MacDonald *et al*. (2008).

1000 ^{14}C yr BP) in the mixed and shortgrass prairie of the U.S. Great Plains. Because the percent of soil carbon derived from C_4 plants "corresponds strongly with summer temperatures as reflected in the soil carbon pool (Nordt *et al*., 2007; von Fischer *et al*., 2008)," they were able to devise a history of the relative warmth of the region over this protracted period (see Figure 4.2.4.7.2.6).

Nordt *et al*.'s data suggest their region of study was slightly warmer during parts of both the Medieval and Roman Warm Periods, and it was significantly warmer during a sizeable portion of the mid-Holocene Thermal Maximum or Climatic Optimum, as it is sometimes called. As to what caused the greater warmth of those earlier periods, Nordt *et al*. observe, "these warm intervals ... exhibit a strong correlation to increases in solar irradiance," as per the irradiance reconstruction of Perry and Hsu (2000).

Whitlock *et al*. (2008) analyzed (at high resolution) geochemical, stable-isotope, pollen, charcoal, and diatom records found in cores obtained from Crevice Lake—located at 45.000°N, 110.578°W—to reconstruct the ecohydrologic, vegetation, and fire history of its watershed for the past 2,650 years and better understand past climate variations at the forest-steppe transition within the canyon of the Yellowstone River in northern Yellowstone National Park (YNP). The seven scientists report their many datasets were "consistent with overall warmer/drier conditions during the Medieval Climate Anomaly," which they note had been variously dated between AD 650 and 1300 in the western United States and Great Plains. They found "the Crevice Lake data suggest a warm interval with dry winters between AD 600 and 850, followed by less dry but still warm conditions between AD 850 and 1100." In addition, they note, "other studies in YNP indicate that trees grew above the present-day treeline and fires were more frequent in the Lamar and Soda Butte drainages between AD 750 and 1150," citing Meyer *et al*. (1995).

Whitlock *et al*. state their data indicate "the last 150 years of environmental history since the formation of YNP have not been anomalous within the range of variability of the last 2650 years, and many of the proxy indicators suggest that 19th and 20th century variability at Crevice Lake was moderate compared with earlier extremes." With the possible exception of the charcoal record, "all of the data show greater variability in the range of ecosystem conditions prior to the establishment of the YNP in 1872." Thus the many parameters measured by Whitlock *et al.* indicate the YNP's twentieth century climate is not unique and suggest much of the Medieval Warm Period was significantly warmer than the Current Warm Period has been to date, given that trees in

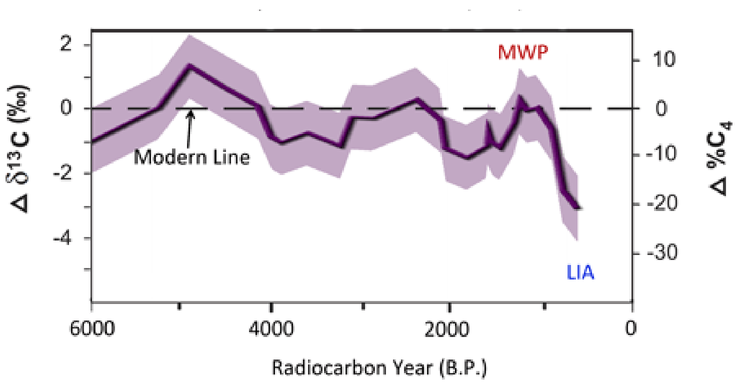

Figure 4.2.4.7.2.6. Buried soil Δδ13C and Δ%C4 from the Great Plains as a proxy for summer temperature. Adapted from Nordt, L., von Fischer, J., Tieszen, L., and Tubbs, J. 2008. Coherent changes in relative C4 plant productivity and climate during the late Quaternary in the North American Great Plains. *Quaternary Science Reviews* **27**: 1600–1611.

some parts of the park grew at higher elevations during the MWP than they do now.

Persico and Meyer (2009) describe their use of "beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park," comparing "the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region." They found "gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP are contemporaneous with increased charcoal accumulation rates in Yellowstone lakes and peaks in fire-related debris-flow activity, inferred to reflect severe drought and warmer temperatures (Meyer *et al*., 1995)." In addition, they note, "the lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly, a time of widespread multi-decadal droughts and high climatic variability in Yellowstone National Park (Meyer *et al*., 1995) and the western USA (Cook *et al*., 2004; Stine, 1998; Whitlock *et al*., 2003)." The lack of evidence for beaver activity 2,200–1,800 cal yr BP is concurrent with the Roman Warm Period. The two researchers conclude the severe droughts of these periods "likely caused low to ephemeral discharges in smaller streams, as in modern severe drought," implying the Medieval and Roman Warm Periods were likely to have been at least as dry and warm as it is today.

Mullins *et al*. (2011) studied two sediment cores extracted from the extreme southern end of Cayuga Lake (~42°25'N, 76°35'W) in central New York (USA), finding "paleolimnological evidence for the Medieval Warm Period (~1.4–0.5 ka), which was warmer and wetter than today." This evidence includes weight percent total carbonate (TC), total organic matter (TOM), non-carbonate inorganic terrigenous matter (TT), carbonate stable isotopes (δ^{18}OTC and δ^{13}CTC), carbon isotope values of total organic matter (δ^{13}CTOM), and fossil types (gastropods, ostracods, bivalves, oogonia) and amounts. All were used to interpret past climate based on their relationship to modern climate data for the Finger Lakes region of the state. They conclude, the "data for central New York suggest a warmer, wetter climate than today."

Routson *et al*. (2011) write, "many southwestern United States high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than those experienced during the historical period (e.g., Woodhouse and Overpeck, 1998; Cook *et al*., 2004, 2010; Meko *et al*., 2007)." They note, "the medieval interval (ca. AD 900 to 1400), a period with relatively warm Northern Hemisphere temperatures, has been highlighted as a period in western North America with increased drought severity, duration and extent (e.g., Stine, 1994; Cook *et al*., 2004, 2010; Meko *et al*., 2007; Woodhouse *et al*., 2010)," and "the mid-12th century drought associated with dramatic decreases in Colorado River flow (Meko *et al*., 2007), and the 'Great Drought' associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region (Douglass, 1929), all occurred during the medieval period."

Routson *et al*. used a new tree-ring record derived from living and remnant bristlecone pine wood from the headwaters region of the Rio Grande River in Colorado (USA), along with other regional records, to evaluate what they describe as "periods of unusually severe drought over the past two millennia (268 BC to AD 2009)." The three researchers report the record they derived "reveals two periods of enhanced drought frequency and severity relative to the rest of the record": "the later period, AD ~1050–1330, corresponds with medieval aridity well documented in other records," and "the earlier period is more persistent (AD ~1–400), and includes the most pronounced event in the ... chronology: a multi-decadal-length drought during the 2nd century." The latter drought "includes the unsmoothed record's driest 25-year interval (AD 148–173) as well as a longer 51-year period, AD 122–172, that has only two years with ring width slightly above the long-term mean." In addition, "the smoothed chronology shows the periods AD 77–282 and AD 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-year record." This second century drought, they note, "impacted a region that extends from southern New Mexico north and west into Idaho."

The researchers note, "reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity," and "available data also suggest that the Northern Hemisphere may have been warm during both intervals." Despite these obviously natural occurrences, Routson *et al*. suggest the southwestern United States may experience similar or even more severe megadroughts in the future as a result of greater warming in response to anthropogenic CO_2 emissions.

Sritairat *et al*. (2012) point out "the mid-Hudson region contains freshwater peatland archives that have not been investigated," suggesting "there is a need to identify this base-line information to assess past anthropogenic activities and climatic patterns in relation to projected shifts in climate and vegetation in the Mid-Hudson Valley region." They explored "how climate and human impacts have influenced plant ecology, invasive species expansion, habitat loss, carbon storage, and nutrient dynamics over the past millennium based on the multiproxy analysis of sediment cores using palynology, macrofossil, sedimentological, and geochemical analyses," working with marsh sediment cores obtained at the National Estuarine Research Reserve at Tivoli Bays on the Hudson Estuary, New York, USA.

The six scientists identified a pre-European settlement period (AD 826–1310) with a "high percentage of *Carya*, a warmth-loving species (Fowells, 1965)," a finding that "supports an increase in temperature."At a depth dated to AD 1087 ± 72, they found a charcoal maximum, referring to it as "a feature that is also found in other Hudson river marsh cores at Piermont (Pederson *et al*., 2005) and Iona (Peteet *et al*., 2006)." This represents, they write, "the warm, dry Medieval Warm Period (MWP)," which they further state was "likely a result of a regional Hudson Valley MWP recorded on a larger spatial scale in other parts of North America and the globe."

The substantial body of real-world evidence for a generally warmer-than-present MWP, at a time when the atmosphere's CO_2 concentration was something on the order of 285 ppm, as opposed to the 400 ppm of today, weighs heavily against the claim of higher atmospheric CO_2 concentrations invariably leading to warmer mean global temperatures. This data-grounded fact provides a concrete reason for rejecting the projections of even the very best mathematical models of how Earth's climate is supposed to operate.

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4.2.4.7.3 Central America

Lachniet *et al*. (2004) generated a high-resolution oxygen-isotope rainfall record of the Central American Monsoon for the Isthmus of Panama from a U/Th-dated stalagmite that spanned the period 180 BC to AD 1310. The work revealed pronounced hydrologic anomalies during medieval times, with the driest conditions occurring between AD 900 and 1310, but especially during the AD 1100-–200 "High Medieval" when western European temperatures were reported to be "anomalously high," as Lachniet *et al*. put it. The seven scientists state, "the correspondence between warm medieval temperatures and dry hydrologic anomalies in Panama supports a large-scale Medieval Climatic Anomaly that may have been global in extent, and involved atmospheric circulation reorganizations that are linked to ENSO."

Hodell *et al*. (1995) examined a sediment core retrieved in 1993 from Lake Chichanacanab in the center of the northern Yucatan Peninsula of Mexico (19°50'-19°57'N, 88°45'-88°46'W), finding evidence of a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800–1000). Subsequently, based on two additional sediment cores retrieved from the same location in 2000, Hodell *et al*. (2001) determined the massive drought likely occurred in two distinct phases (750–875 and 1000–1075). Hodell *et al*. (2005) returned to Lake Chichanacanab in March 2004 to retrieve additional sediment cores in some of the deeper parts in the lake, with multiple cores being taken from its deepest point.

Depth profiles of bulk density data were obtained by means of gamma-ray attenuation, as were profiles of reflected red, green, and blue light via a digital color line-scan camera. The researchers report, "the data revealed in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization." They also showed "the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions," which "included an early phase (ca 770–870) and late phase (ca 920–1100)." They report, "the bipartite drought history inferred from Chichancanab is supported by oxygen isotope records from nearby Punta Laguna," and "the general pattern is also consistent with findings from the Cariaco Basin off northern Venezuela (Haug *et al*., 2003), suggesting that the Terminal Classic Drought was a widespread phenomenon and not limited to north-central Yucatan." It appears the Terminal Classic Drought that led to the demise of Mayan civilization likely occurred during the climatic transition between the Dark Ages Cold Period and the Medieval Warm Period, when increasing tempera-tures may have exacerbated land water loss via evaporation in the midst of a prolonged period of significantly reduced precip-itation.

Almeida-Lenero *et al*. (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala (19°03'N, 99°18'W) and nearby Lake Quila (19°04'N, 99°19'W) in the central Mexican highlands about 65 km southwest of Mexico City. They determined it was generally more humid in the central Mexican highlands during the mid-Holocene than at present. Thereafter, there was a gradual drying of the climate; their data from Lake Zempoala indicate "the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene," and this interval of 200 years "coincides with the collapse of the Maya civilization." They report their data from Lake Quila were also "indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP." They state, "climatic aridity during this time was also noted by Metcalfe *et al*. (1991) for the Lerma Basin [central Mexico]," "dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982)," and "dry conditions were also reported for [Mexico's] Zacapu Basin (Metcalfe, 1995) and for [Mexico's] Yucatan Peninsula (Curtis *et al*., 1996, 1998; Hodell *et al*., 1995, 2001)."

Barron and Bukry (2007) analyzed high-resolution records of diatoms and silicoflagellate assemblages spanning the past 2,000 years derived from sediment cores extracted from three sites on the eastern slope of the Gulf of California, comprising core BAM80 E-17 retrieved at 27.92°N, 111.61°W; core NH01-21 retrieved at 26°17.39'N, 109°55.24'W; and core NH01-26 retrieved at 24°16.78'N, 108°11.65W. In all three cores, the relative abundance of *Azpeitia nodulifera* (a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures) was found to be far greater during the Medieval Warm Period than at any other time over the 2,000-year period studied, and during the Current Warm Period its relative abundance was lower than the 2,000-year mean, also in all three of the sediment cores (Figure 4.2.4.7.3.1). In addition, the first of the cores exhibited elevated *A. nodulifera*

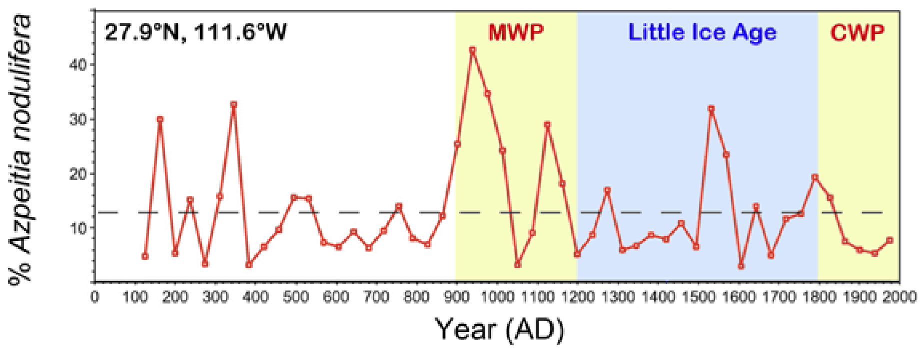

Figure 4.2.4.7.3.1. Relative abundance of Azpeitia nodulifera, a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures, derived from sediment cores extracted from three sites on the eastern slope of the Gulf of California. Adapted from Barron, J.A. and Bukry, D. 2007. Solar forcing of Gulf of California climate during the past 2000 yr suggested by diatoms and silicoflagellates. *Marine Micropaleontology* **62**: 115–139.

abundances from the start of the record to about AD 350, during the latter part of the Roman Warm Period, as well as between AD 1520 and 1560. By analyzing radiocarbon production data, the two researchers found the changes in climate they identified likely were driven by solar forcing.

Metcalfe and Davies (2007) synthesized the findings of a variety of paleoclimate studies based on analyses of the sediment records of several crater lakes and lakes formed by lava dams across the Trans Mexican Volcanic Belt of central Mexico with an absolute chronology provided by radiocarbon dates extending back to 1,500 ^{14}C yr BP. Noting the degree of coherence among the records is "remarkable," Metcalf and Davis report, "dry conditions, probably the driest of the Holocene, are recorded over the period 1,400 to 800 ^{14}C yr BP (ca. AD 700–1200)." They also observe "the present day climate of central Mexico is typical of most of the country." The researchers tate their work is "consistent with results from the Yucatan Peninsula (Hodell *et al*., 1995, 2005) … and from the Cariaco basin (Haug *et al*., 2003) and the Isthmus of Panama (Lachniet *et al*., 2004)." In addition, Mayewski *et al*. (2004) have identified the central portion of this period (AD 800 to 1000) as a time of truly global anomalous climate.

Thus, Metcalfe and Davies provide convincing evidence that one of the strongest manifestations of the Medieval Warm Period throughout most of Mexico was a major lack of moisture, which in this particular part of the world delineates the Medieval Warm Period better than the epoch's primary defining characteristic of elevated temperature.

Hodell *et al*. (2007) inferred "the Holocene paleoclimate history of the northeastern Yucatan Peninsula by comparing physical and chemical properties in two sediment cores from Lake Punta Laguna," located approximately 20 km NNE of Coba, discussing "the potential implications for Maya cultural transformation." They report the Terminal Classic Collapse of 750–1050 A.D., which they describe as "the greatest cultural discontinuity prior to Spanish contact," can "be viewed as a series of transformations, occurring first in the south during the late eighth and ninth centuries A.D., followed by a similar decline in the north in the tenth century A.D." They also found evidence for "lower lake level and drier climate at about the same time as each major discontinuity in Maya cultural history."

According to the three researchers, "the fact that both major climatic changes and cultural transformations occurred in the Terminal Classic Period between 750 and 1050 A.D. is probably not coincidental." Global weather patterns indeed may have changed in such a way over this period that the recurring multi-year dry spells characteristic of the Terminal Classic Period became increasingly severe and difficult for the Maya to bear, likely leading to the civilization's collapse at the very peak of the global Medieval Warm Period.

Polk *et al*. (2007) analyzed environmental changes on Belize's Vaca Plateau via "vegetation reconstruction using $\delta^{13}C$ values of fulvic acids extracted from cave sediments," which provide "a proxy record of Maya alteration of the environment through agricultural practices," in conjunction with "speleothem carbon and oxygen isotope data from another nearby cave in the study area" that "provide information regarding climate variability."

Starting at approximately AD 500, according to the three U.S. researchers, increasingly negative $\delta^{13}C$ values in the sediment record indicate "the declining practice of agriculture," which they say is "characteristic of a C_3-dominated environment receiving little contribution from the isotopically heavier C_4 agricultural plants." This inference makes sense because the period of initial agricultural decline coincides with the well-known Maya Hiatus of AD 530 to 650, which was driven by an increasing "lack of available water resources needed to sustain agriculture," and the study area "would likely have been among the first sites to be affected by aridity due to its naturally well-drained upland terrain, causing a shift away from agricultural land use that preceded [that of] many other lowland areas."

Polk *et al*. report their $\delta^{13}C$ values indicate that as early as AD 800 the Vaca Plateau "was no longer used for agriculture, coinciding with the Terminal Classic Collapse" of the Maya, which Hodell *et al*. (2007) identified as taking place between AD 750 and 1050, indicating the Ix Chel archaeological site on the Vaca Plateau was one of the first to bear witness to the demise of the Maya people.

These discoveries of Polk *et al*. are just another example of the devastating human consequences of the catastrophic droughts that plagued many parts of North, Central, and northern tropical South America during the global Medieval Warm Period. They also constitute yet another important testament to the reality of the MWP and its global reach.

Dominguez-Vazquez and Islebe (2008) derived a 2,000-year history of regional drought using radiocarbon dating and pollen analyses of a sediment core retrieved from the shore of Naja Lake (16°59'27.6"N, 91°35'29.6"W), located near the Lacandon Forest Region in the state of Chiapas in southeastern Mexico, inhabited by the Maya since the early Formative Period (ca. 1,000 BC). The researchers write, "a marked increase in *Pinus* pollen, together with a reduction in lower montane rain forest taxa, is interpreted as evidence for a strong, protracted drought from 1260 to 730 years BP," which they characterize as "the most severe" of the record. They note, "the drought coincides with the Maya classic collapse and represents the most pronounced dry period of the last 2,000 years in the Lacandon area."

Thus, much as the higher temperatures of the Medieval Warm Period in Greenland benefited the Vikings, its greater dryness in southeastern Mexico cursed the Maya, who had called that region home for close to 2,000 years. This contrast exemplifies how millennial-scale climate change can have vastly different effects on human societies in different parts of the world. It is also equally clear these changes of the past occurred independently of any changes in the air's CO_2 content, and if the world is in the initial stages of a new warming phase of this cycle, both positive and negative impacts can be expected.

Escobar *et al*. (2010) used sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula to "(1) investigate 'within-horizon' stable isotope variability ($\delta^{18}O$ and $\delta^{13}C$) measured on multiple, single ostracod valves and gastropod shells, (2) determine the optimum number of individuals required to infer low-frequency climate changes, and (3) evaluate the potential for using intra-sample $\delta^{18}O$ variability in ostracod and gastropod shells as a proxy measure for high-frequency climate variability." The five researchers state the resulting data "allow calculation of mean isotope values and thus provide a rough estimate of the low-frequency variability over the entire sediment sequence." These results indicate "relatively dry periods were persistently dry whereas relatively wet periods were composed of wet and dry times."

These findings "confirm the interpretations of Hodell *et al*. (1995, 2007) and Curtis *et al*. (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period." The scientists determined the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the past 3,000 years, but also a persistently dry period. They note, "the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability."

Brunelle *et al*. (2010) collected sediments from a cienega (a wet, marshy area where groundwater bubbles to the surface) located at approximately 31.3°N, 109.3°W in the drainage of Black Draw Wash/Rio de San Bernardino of southeastern Arizona (USA) and northeastern Sonora (Mexico) during the summers of 2004 and 2005, sampling the incised channel wall of the Rio de San Bernardino arroyo and the cienega surface of the San Bernardino National Wildlife Refuge "for charcoal analysis to reconstruct fire history," as well as pollen data to infer something about climate. The team of U.S. and Mexican researchers report "preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity," and the results from the fire reconstruction "show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly." During the latter period, from approximately AD 900 to 1260, "background charcoal reaches the highest level of the entire record and fire peaks are frequent," after which, they report "the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al*., 2004)."

Figueroa-Rangel *et al*. (2010) constructed a 1,300-year history of the cloud forest vegetation dynamics of the Sierra de Manantlan Biosphere Reserve (SMBR) in west-central Mexico via analyses of fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35'32"N, 104°16'56"W). This reconstruction revealed "during intervals of aridity, cloud forest taxa tend to become reduced," whereas "during intervals of increased humidity, the cloud forest thrives." The three researchers inferred from their reconstruction a major dry period that lasted from approximately AD 750 to 1150 in the SMBR.

They write, "results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region; in central Mexico (Metcalf and Hales, 1994; Metcalfe, 1995; Arnauld *et al*., 1997; O'Hara and Metcalfe, 1997; Almeida-Lenero *et al*., 2005; Ludlow-Wiechers *et al*., 2005; Metcalfe *et al*., 2007); lowlands of the Yucatan Peninsula (Hodell *et al*., 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug *et al*., 2003)." They also note "the causes associated to this phase of climate change have been attributed to solar activity (Hodell *et al*., 2001; Haug *et al*., 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe *et al*., 2000; Hodell *et al*., 2005a,b; Berrio *et al*., 2006) and to ENSO variability (Metcalfe, 2006)." The timeframe of this significant dry period coincides well with the broad central portion of the Medieval Warm Period, and this correspondence further harmonizes with the dry period's temporal association with enhanced solar activity and a southward shift of the ITCZ.

Focusing on the North American countries south of the United States southern border, the studies reviewed here clearly demonstrate the existence of a Medieval Warm Period far removed from the North Atlantic Ocean, contrary to the IPCC's dismissal of the MWP as a minor, regional phenomenon. To the contrary, the MWP was global in extent, as demonstrated by data obtained on all of Earth's continents, and it was characterized by temperatures generally higher than those of the recent past and the present, in an atmosphere with a CO_2 concentration of only 285 ppm, compared to the 400 ppm of today.

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4.2.4.8 Oceans

As indicated in the introduction of Section 4.2.4, data presented in numerous peer-reviewed scientific studies reveal the existence of a global Medieval Warm Period (MWP) that occurred approximately 1,000 years ago when atmospheric CO_2 concentrations were approximately 30 percent lower than they are today. This natural fluctuation in climate is likely the product of a millennial-scale oscillation responsible for ushering in the relative warmth of the present day. This subsection highlights work that has documented the MWP, and various characteristics of it, in the world's oceans.

4.2.4.8.1 The Past Several Millennia

Gagan *et al*. (1998) used a double-tracer technique based on Sr/Ca and $^{18}O/^{16}O$ ratios in the skeletal remains of corals from Australia's Great Barrier Reef to infer climatic conditions for that region about 5,350 years ago. Impressed with their use of such coupled data, which allowed them to more accurately determine sea surface temperatures (SSTs) than had been possible in the past, Beck (1998) stated in his commentary on their paper that the new approach "promises to elucidate many important new clues about the dynamics of the coupled ocean-atmosphere-climate system for climate modelers to digest."

Gagan *et al*.'s work indicated the tropical ocean surface some 5,350 years ago, when there was much less CO_2 in the air than there is today, was 1.2°C warmer than the mean that prevailed throughout the early 1990s. This finding accorded well with terrestrial pollen and tree-line elevation records from elsewhere in the tropical Pacific for the entire period from 7,000 to 4,000 years ago. In addition, their work suggests the higher tropical SSTs of that time likely enhanced evaporation from the tropical Pacific, and the extra latent heat and moisture thereby exported to higher latitudes may have helped to maintain the equable climates known to have characterized the extra-tropics during this time.

McManus *et al*. (1999) examined a deep-sea sediment core from the eastern North Atlantic Ocean that included the last five glacial-interglacial cycles. They noted significant temperature oscillations throughout the record, which were of much greater amplitude during glacial as opposed to interglacial periods. SSTs, for example, oscillated between 1° and 2°C during warm interglacials, but varied between 4° and 6°C during colder glacial times. They conclude climatic variability on millennial time scales "has thus been the rule, rather than the exception." It is likely the warming of the last century or so was simply the most recent manifestation of a naturally recurring phenomenon unrelated to the concurrent increase in the atmosphere's CO_2 concentration. In addition, McManus *et al*.'s findings clearly contradict the contention that any future global warming will result in greater, and therefore more harsh, temperature extremes; their half-million-year record clearly indicates temperature variability during warmer times is more muted than it is during colder times.

Adding 50,000 years to the interval investigated by McManus *et al*., Herbert *et al*. (2001) analyzed proxy SSTs over the past 550,000 years via data obtained from several marine sediment cores taken along the western coast of North America, from 22°N at the southern tip of the Baja Peninsula to 42°N off the coast of Oregon. They found "the previous interglacial produced surface waters several degrees warmer than today," such that "waters as warm as those now at Santa Barbara occurred along the Oregon margin." Their data indicate the peak SSTs of the current interglacial were 1° to 4°C cooler than the peak SSTs of all four of the preceding interglacial periods.

Raymo *et al*. (1998) studied physical and chemical characteristics of an ocean sediment core retrieved from a site south of Iceland. They found millennial-scale oscillations of climate were occurring more than one million years ago in a region of the North Atlantic that has been shown to strongly influence circum-Atlantic, and possibly global, climate. These oscillations appeared to be similar in character and timing to the Dansgaard-Oeschger cycles of the most recent glacial epoch.

Because the climate of the early Pleistocene was too warm to support the growth and development of the large, 100,000-year ice sheets characteristic of the late Pleistocene, and because similar millennial-scale climate oscillations are evident in both time periods, Raymo *et al.* conclude millennial-scale climate oscillations "may be a pervasive and long-term characteristic of Earth's climate, rather than just a feature of the strong glacial-interglacial cycles of the past 800,000 years." Since the millennial-scale climate oscillations of both periods have not been attributed to variations in atmospheric CO_2 concentration, there would appear to be little reason to attribute the warming of the past century or so to the concurrent increase in the atmosphere's CO_2 concentration, or to expect any further rise in CO_2 content to trigger significant warming.

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4.2.4.8.2 The Past Few Centuries

In order to understand the present—and potentially predict the future—it is helpful to have a correct understanding of the past, and nowhere is this more important than in the ongoing debate over the impact of anthropogenic CO_2 emissions on global climate. In this summary, we review what has been learned about this subject based on proxy sea surface temperature data pertaining to the past few centuries.

Fjellsa and Nordberg (1996) derived a history of the Holocene distribution of the dinoflagellate *Gymnodinium catenatum* from an ocean sediment core extracted from the Kattegat region of the North Sea between Sweden and Denmark (56°32'48" N, 12°11'15" E). This work revealed an early abundance of the species at about 4,300–4,500 yr BP. Then, in connection with what they called a "climatic deterioration, the species decreased abruptly and subsequently disappeared." It reestablished its presence some time later and, as they describe it, "occurred in massive 'blooms' during the so-called mediaeval warm epoch round about 700–800 yr BP." They add, "at the time of the so-called Little Ice Age, approximately 300 yr BP, *G. catenatum* again became extinct in the Kattegat area."

Fjellsa and Nordberg report "there appears to be a close relationship between climatic fluctuations and the presence and abundances of *G. catenatum*, which from its present ecology is considered a warmer water species." They conclude the two bloom periods were "characterized as warmer periods with climatic optima correlated to the peak phases," noting "the most massive blooms took place during the so-called 'Medieval warm epoch.'"

The two researchers also report, "cysts from *G. catenatum* have been found in the surface sediments from the Danish coast bordering the Kattegat (Ellegaard *et al*., 1993)," but they say they "do not know if *G. catenatum* has lived as a small part of the plankton since the 'Little Ice Age,' or if the species has been re-introduced by the current system or via ships' ballast tanks." And they note "there is also a possibility that the species has become re-established in conjunction with global warming during the past 80 years." The AD 1996 abundance of the key dinoflagellate was nowhere near that of the "massive blooms" of the Medieval Warm Period. Hence, we date the MWP in the Kattegat region of the North Sea to the period AD 1200–1400, concluding the peak warmth of the MWP was greater than that of the CWP so far.

Keigwin (1996) noted "it is important to document natural climate variability in order to understand the effects of anthropogenic forcing." Working with two subcores of a sediment box core retrieved from 33°41.6'N, 57°36.7'W of the undulating plateau of the northeast Bermuda Rise, he measured the oxygen isotope ratios ($\delta^{18}O$) of the white variety of the planktonic foraminifera *Globigerinoides ruber*, which lives year-round in the upper 25 meters of the northern Sargasso Sea and has a relatively constant annual mass flux and shell flux to the sediments. Calibrating these data against temperature and salinity data obtained at Ocean Station "S" (32°N, 62°30'W) over the prior 42 years, he determined "temperature accounts for about two-thirds of the isotopic signal, whereas salinity accounts for one-third." He then calculated sea surface temperatures (SSTs) of the prior three millennia, after which he "stacked the temperature proxy data from the two subcores by averaging results in 50-year bins," obtaining the results shown in Figure 4.2.4.8.2.1.

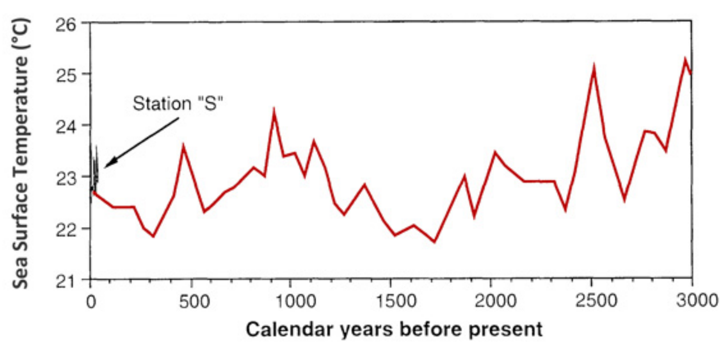

Figure 4.2.4.8.2.1. Fifty-year averages of mean annual sea surface temperature calculated from the $\delta^{18}O$ data of the two Bermuda Rise sediment subcores, together with the mean annual SSTs measured at Ocean Station "S" over the period 1954–1996. Adapted from Keigwin, L. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science* **274**: 1504–1508.

As can be seen from this figure, and as Keigwin stated, the northern Sargasso Sea SST "was ~1°C cooler than today ~400 years ago (the Little Ice Age) and 1700 years ago [the Dark Ages Cold Period], and ~1°C warmer than today 1000 years ago (the Medieval Warm Period)." He notes "over the course of three millennia, the range of SST variability in the Sargasso Sea is on the order of twice that measured over recent decades" and concludes "at least some of the warming since the Little Ice Age appears to be part of a natural oscillation." In addition, "because the changes described here for surface waters over the Bermuda Rise are probably typical of a large part of the western Sargasso Sea, they most likely reflect climate change on the basin or hemispheric scale."

Andren *et al*. (2000) conducted an extensive analysis of changes over time in siliceous microfossil assemblages and chemical characteristics of various materials found in a well-dated sediment core obtained from the Bornholm Basin in the southwestern Baltic Sea. The data revealed the existence of a period of high primary production at approximately AD 1050. In addition, the diatoms they identified were warm water species such as *Pseudosolenia calcar-avis*, which they describe as "a common tropical and subtropical marine planktonic species" that "cannot be found in the present Baltic Sea." They also note what they call the Recent Baltic Sea Stage, which began about AD 1200, started at a point when there was "a major decrease in warm water taxa in the diatom assemblage and an increase in cold water taxa, indicating a shift towards a colder climate," which they associate with the Little Ice Age.

These data clearly indicate there was a period of time in the early part of the past millennium when the climate in the area of the southwestern Baltic Sea was significantly warmer than it is today, as the sediment record of that time and location contained several warm water species of diatoms, some of which can no longer be found there. This period of higher temperatures, in the words of the three researchers, fell within "a period of early Medieval warmth dated to AD 1000–1100," which "corresponds to the time when the Vikings succeeded in colonizing Iceland and Greenland." This period was one of strikingly high oceanic primary productivity, demonstrating what seems to be the case with both ecosystems and human societies; i.e., warmer is better.

Keigwin and Boyle (2000) discussed the evidence for a climate oscillation with a return period of 1,500 to 2,000 years that is evident in proxy climate data pertaining to the last deglaciation and has continued (with reduced amplitude) through the Holocene, along with its association with contemporaneous changes—demonstrable for the last deglaciation but tenuous for the Holocene—in the thermohaline circulation of the North Atlantic Ocean. The Little Ice Age was the most recent cold phase of this persistent climatic phenomenon that may be induced by variations in the production rate of North Atlantic Deep Water. As the two researchers report, "mounting evidence indicates that the LIA was a global event, and that its onset was synchronous within a few years in both Greenland and Antarctica." In the Northern Hemisphere, for example, they state, it was expressed as a 1°C cooling between approximately 1500 and 1900 AD, with a cooling of approximately 1.7°C in Greenland.

Although the immediate cause or causes of the phenomenon have yet to be definitively identified, there is little question that Earth's climate oscillates globally on a millennial time-scale independent of the activities of man, and the most recent cold phase of that natural oscillation was what we call the Little Ice Age, centered on approximately AD 1700 and lasting until about AD 1900. Thus it was only to be expected that temperatures would have risen over the past century or so, and they may continue to rise even further until a warm epoch analogous to the Medieval Warm Period is reached. It is unjustified to conclude, as the IPCC does, that the majority of any warming that may currently be occurring is due to anthropogenic CO_2 emissions.

Linsley *et al*. (2000) retrieved a core of continuous coral from a massive colony of *Porites lutea* on the southwest side of Rarotonga in the Cook Islands, within which they measured Sr/Ca ratios on 1-mm sections spanning the entire core (representing 271 years of growth), as well as $\delta^{18}O$ values at the same resolution from 1726 to 1770 and from 1950 to 1997. The latter interval was used for calibration purposes and utilized Integrated Global Ocean Service System Products SST data. This analysis revealed a quarter-century period centered on about the year 1745 when SSTs in the vicinity of Rarotonga were at least 1.5°C warmer than they are today.

Winter *et al*. (2000) determined SSTs for the periods 1700–1705, 1780–1785, and 1810–1815 from a study of oxygen isotope data obtained from coral skeletons of *Montastrea faveolata* located on the southwestern shore of Puerto Rico. Similar isotope data obtained for the period 1983–1989 and contemporary SSTs directly measured at the University of Puerto Rico's marine station at La Parguera were used to calibrate the temperature reconstruction technique and provide a current baseline against which to compare the researchers' Little Ice Age results. The SSTs they derived were significantly cooler during the three Little Ice Age periods than they were at the time of their study. They report their results indicate "the Caribbean experienced cooling during the Little Ice Age with temperature estimated to be at least 2°–3° cooler than found during the present decade."

The data presented by Winter *et al*., as well as the data contained in several papers they cite, led them to conclude "the Little Ice Age may have been more global in extent than previously expected." It also may have been much colder than previously believed, for they point out the cooling suggested by their data "represents about half of the sea surface temperature cooling recorded in Barbados corals during the Last Glacial Maximum."

Doose-Rolinski *et al*. (2001) analyzed a complete and annually laminated sediment core extracted from the bed of the northeastern Arabian Sea just south southeast of Karachi, Pakistan, using oxygen isotopes of planktonic foraminifera and measurements of long-chain alkenones to derive a detailed sea surface temperature and evaporation history of the area. They found the greatest temperature fluctuations of the 5,000-year record occurred between 4,600 and 3,300 years ago and between 500 and 200 years ago, which were also the coldest periods of the record. Of the latter interval, they note, "in northern and central Europe this period is known as the 'Little Ice Age.'" They state their results confirm the "global effects" of this unique climatic change. Also apparent in their temperature history is a period of sustained warmth that prevailed between about 1,250 and 950 years ago, corresponding with the Medieval Warm Period of northern and central Europe.

de Garidel-Thoron and Beaufort (2001) reconstructed a 200,000-year history of primary productivity (PP) in the Sulu Sea north of Borneo, based on abundances of the coccolithophore *Florisphaera profunda*, which was measured in a 36-meter giant piston core retrieved from a depth of 3,600 meters. Three time-slices were explored in detail in order to determine high-frequency cycles in the PP record: one from 160 to 130 ka, one from 60 to 30 ka, and one from 22 to 4.1 ka. The finest-scale repeatable feature observed in all three time-slices was a climate-driven PP oscillation with a mean period of approximately 1,500 years.

The two researchers state they cycle's occurrence in the three different time-slices suggests "a common origin and an almost stationary signal across different climatic conditions." They also note the PP cycle's similarity to the 1,470-year temperature cycle observed by Dansgaard *et al*. (1984) in the Camp Century $\delta^{18}O$ ice core record, the ~1500-year $\delta^{18}O$ and chemical markers cycles observed by Mayewski *et al*. (1997) in the Summit ice core, the 1,470-year climate cycle found by Bond *et al*. (1997, 2001) in North Atlantic deep-sea cores, and the 1500-year climate cycle found by Campbell *et al*. (1998) in an Alaskan lake. These observations led them to suggest there was "a common origin" for the documented cyclicity in the climate of both high and low latitudes.

Hendy *et al*. (2002) reconstructed a 420-year SST history based on Sr/Ca measurements of several coral cores taken from massive *Porites* colonies in the central portion of Australia's Great Barrier Reef. The earliest portion of this region's reconstructed temperature history, from 1565 to about 1700, corresponds to the coldest period of the Little Ice Age as recorded in the Northern Hemisphere. Five-year blocks of mean Great Barrier Reef SSTs during this cold period were sometimes 0.5 to 1.0°C or more below the region's long-term mean. Over the following century, however, South Pacific SSTs were much warmer, as were temperatures in the Northern Hemisphere. In the South Pacific, in fact, SSTs during this period were consistently as warm as—and many times even warmer than—those of the early 1980s, where the coral record ended. During the late 1800s, the South Pacific once again experienced colder conditions that coincided with the "last gasp" of the Little Ice Age in the Northern Hemisphere, after which the Current Warm Period made its presence felt in both regions. That Hendy *et al*. found mid-eighteenth century South Pacific SSTs to be as warm as or even warmer than the final years of the twentieth century suggests the climate of the modern world is in no way unusual, unnatural, or unprecedented.

The mid-eighteenth century warmth of the tropical and subtropical South Pacific Ocean occurred at essentially the same time as the significant peak in Northern Hemispheric temperature that is strikingly evident in the data of Jones *et al*. (1998) and reproduced in the paper of Hendy *et al*. Thus if the data of Hendy *et al*. and Linsley *et al*. (2000 cited earlier) are representative of the great expanse of Southern Hemispheric ocean, the mid-eightreenth century mean temperature of the entire globe may have been about the same as it is now.

Roncaglia (2004) analyzed variations in organic matter deposition from approximately 6,350 cal yr BC to AD 1,430 in a sediment core extracted from the Skalafjord, southern Eysturoy, Faroe Islands to assess climatic conditions in that part of the North Atlantic in the mid- to late-Holocene. She discovered an increase in structured brown phytoclasts, plant tissue, and sporomorphs in sediments dating to ca. AD 830–1090, which she considered indicative of "increased terrestrial influx and inland vegetation supporting the idea of improved climatic conditions." In addition, she reports high "total dinoflagellate cyst concentration and increased absolute amount of loricae of tintinnid and planktonic crustacean eggs occurred at ca. AD 830–1090." She concludes these observations "may suggest increased primary productivity in the waters of the fjord," citing Lewis *et al*. (1990) and Sangiorgi *et al*. (2002). She reports the "amelioration of climate conditions" that promoted the enhanced productivity of both land and sea at this time "may encompass the Medieval Warm Period in the Faroe region."

Providing a longer and different proxy temperature record from the Northern Hemisphere, Jacoby *et al*. (2004) extracted cores from century-old oak trees growing within one km of the Pacific Ocean on Kunashir Island (the southernmost large island in the Kurile Island chain belonging to Russia, located between the Sea of Okhotsk and the northwest Pacific Ocean) and developed them into a four-century tree-ring width index series that was correlated strongly with island summer air temperature. The scientists report, "the recorded temperature data and the tree-ring data show similar correlation patterns with sea-surface temperatures of the North Pacific." They found "the tree-ring series explains more than 33% of the variance of the July–September Pacific Decadal Oscillation and has similar spectral properties, further supporting the concept of multidecadal variation or shifts in North Pacific climate, for four centuries."

The Kunashir June–September mean maximum temperature reconstruction exhibited no long-term trend (neither cooling nor warming) over the entire period from 1600 to 2000, nor did it show any net temperature change over the twentieth century. The peak warmth of the past hundred years occurred right at the mid-century mark, after which temperatures decreased considerably and ended up right about where they started the century.

Lund and Curry (2004) write, "while the Florida Current-Gulf Stream system is arguably one of the most studied features in modern oceanography, almost nothing is known about its behavior on centennial to millennial timescales." Two researchers analyzed planktonic foraminiferal $\delta^{18}O$ time series obtained from three well-dated sediment cores retrieved from the seabed near the Florida Keys (24.4°N, 83.3°W) that covered the past 5,200 years. They report the isotopic data from the three cores indicate "the surface Florida Current was denser (colder, saltier or both) during the Little Ice Age than either the Medieval Warm Period or today," and "when considered with other published results (Keigwin, 1996; deMenocal *et al*., 2000), it is possible that the entire subtropical gyre of the North Atlantic cooled during the Little Ice Age ... perhaps consistent with the simulated effects of reduced solar irradiance (Rind and Overpeck, 1993; Shindell *et al*., 2001)." In addition, they note, "the coherence and phasing of atmospheric ^{14}C production and Florida Current $\delta^{18}O$ during the Late Holocene implies that solar variability may influence Florida Current surface density at frequencies between 1/300 and 1/100 years." This evidence confirms centennial- and millennial-scale climatic variability is explained by similar-scale variability in solar activity, much as Bond *et al*. (2001) found for ice-rafting variability in the subpolar North Atlantic, further suggesting there is no need to use the historical increase in the air's CO_2 content to explain the increase in temperature that marked Earth's transition from the Little Ice Age to the Current Warm Period.

Asami *et al*. (2005) developed a 213-year (1787–2000) monthly resolved time series of carbon and oxygen isotope data obtained from a coral core retrieved from a *Porites labata* colony located on the northwestern coast of Guam, where the colony had been exposed to open sea surface conditions over the entire period of its development. They determined "the early 19th century (1801–1820) was the coolest in the past 210 years, which is consistent with sea surface temperature [SST] reconstructions derived from a $\delta^{18}O$ coral record from New Caledonia (Crowley *et al*., 1997)." This period, they write, "was characterized by a decrease in solar irradiance (Lean *et al*., 1995; Crowley and Kim, 1996) and by a series of large volcanic eruptions in 1808–1809 and 1818–1822 (Crowley *et al*., 1997)." From that point on, they report, "the long-term $\delta^{18}O$ coral trend is characterized by its overall depletion throughout the period," indicative of a gradual warming of approximately 0.75°C.

This temperature history from a tropical region of the globe is essentially identical to the extratropical Northern Hemispheric temperature record of Esper *et al*. (2002), which stands in stark contrast to temperature reconstructions of Mann *et al*. (1998, 1999), which do not depict the existence of the Little Ice Age. The latter multi-century cool period is clearly manifest at the beginning of the Guam record, and it is evident at about the same time in the New

Caledonia record. The Guam SST history also differs from the Mann *et al*. temperature history depicting close to continuous warming from about 1815, just as the Esper *et al*. record does, whereas the Mann *et al*. record does not depict any warming until after 1910, about a century later. The 0.75°C rise in temperature from the start of the warming until the end of the twentieth century observed in the Guam record is not at all unusual, since it begins at one of the coldest points of the coldest multi-century period of the entire Holocene, the current inter-glacial.

Dima *et al*. (2005) note previous investigations of a Rarotonga coral-based SST reconstruction from the Cook Islands in the South Pacific Ocean focused on documenting and interpreting decadal and interdecadal variability without separating distinct modes of variability within this frequency band (Linsley *et al*. 2000, 2004; Evans *et al*. 2001). They reanalyzed the original coral record using Singular Spectrum Analysis to determine the dominant periods of multi-decadal variability in the series over the period 1727–1996. Their analysis revealed two dominant multi-decadal cycles, with periods of about 25 and 80 years. These modes of variability were found to be similar to multi-decadal modes observed in the global SST field of Kaplan *et al*. (1998) for the period 1856–1996. The ~25-year cycle was found to be associated with the Pacific Decadal Oscillation, whereas the ~80-year cycle was determined to be "almost identical" to a pattern of solar forcing found by Lohmann *et al*. (2004), which, according to Dima *et al*., "points to a possible solar origin" of this mode of SST variability. The results of their study provide an intriguing glimpse into the cyclical world of oceanic climatic change, demonstrating the existence of two strong multi-decadal modes of SST variability that are clearly natural in origin. Before SST trends can be attributed to anthropogenic activities, they must have all known modes of natural variability removed from them.

Newton *et al*. (2006) analyzed a sediment core collected at 5°12.07'S, 117°29.20'E in the Indo-Pacific Warm Pool (one of the warmest regions in the modern oceans) for planktonic foraminiferal (*Globigerinoides ruber*) Mg/Ca and $\delta^{18}O$ data to derive high-resolution summer sea surface temperature (SST) and salinity histories extending back about a thousand years. They report, "the warmest temperatures and highest salinities occurred during the Medieval Warm Period," which lasted from about AD 1020 to1260. Over this period, summer SSTs averaged about 29.7°C, as best as can be determined from their graph of the data (Figure 4.2.4.8.2.2), with a peak of about 30.9°C in the vicinity of AD 1080. These values are to be compared with the region's average modern summer SST of 29.0°C, significantly lower than that of the Medieval Warm Period. They also found "the coolest temperatures and lowest salinities occurred during the Little Ice Age," the lowest temperatures of which occurred "around AD 1700, during the period of reduced solar intensity known as the Maunder Minimum," when summer SSTs "were 1.0–1.5°C cooler than present," presumably due to the lower solar activity of that period. Newton *et al*. state their data from the Makassar Strait of Indonesia clearly indicates "climate changes during the Medieval Warm Period and Little Ice Age were not confined to the high latitudes" nor to countries bordering the North Atlantic Ocean.

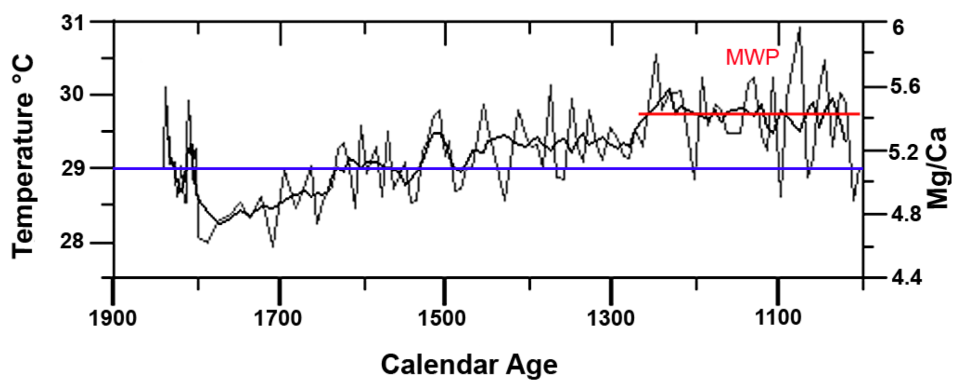

Figure 4.2.4.8.2.2. Mg/Ca-derived summer sea surface temperatures (SST) in the Indo-Pacific Warm Pool. The blue line represents the modern average SST value of 29°C. Adapted from Newton, A., Thunell, R., and Stott, L. 2006. Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium. *Geophysical Research Letters* **33**: 10.1029/2006GL027234.

Richey *et al*. (2007) note the variability of the hemispheric temperature reconstructions of Mann and Jones (2003) over the past one to two thousand years were “subdued (≤0.5°C)” and their low-amplitude reconstructions contrast “with several individual marine records that indicate that centennial-scale sea surface temperature (SST) oscillations of 2–3°C occurred during the past 1-2 k.y. (i.e., Keigwin, 1996; Watanabe *et al*., 2001; Lund and Curry, 2006; Newton *et al*., 2006).” They also contrast with “tree-ring and multiproxy reconstructions designed to capture multicentennial-scale variability (e.g., Esper *et al*., 2002; Moberg *et al*., 2005),” which further suggests “the amplitude of natural climate variability over the past 1 k.y. is >0.5°C,” the scientists state. They constructed a continuous decadal-scale-resolution record of climate variability over the past 1,400 years in the northern Gulf of Mexico from a box core recovered in the Pigmy Basin, northern Gulf of Mexico (27°11.61’N, 91°24.54’W), based on climate proxies derived from paired analyses of Mg/Ca and δ^{18}O in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages.

The four researchers report two multi-decadal intervals of sustained high Mg/Ca indicated Gulf of Mexico sea surface temperatures (SSTs) were as warm as, or warmer than, near-modern conditions between 1,000 and 1,400 yr BP (during the MWP), and foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr BP) indicated SSTs were 2–2.5°C below modern SSTs. In addition, they found the four minima in the Mg/Ca record between 900 and 250 yr. B.P. corresponded in time with the Maunder, Sporer, Wolf, and Oort sunspot minima.

Barron and Bukry (2007) developed high-resolution records of diatoms and silicoflagellate assemblages spanning the past 2,000 years, from analyses of a sediment core extracted from the Carmen (26°17.39’N, 109°55.24’W), Guaymas (27.92°N, 111.61°W), and Pescadero Basins (24°16.78’N, 108°11.65W) of the Gulf of California. The relative abundance of *Azpeitia nodulifera*, a tropical diatom whose presence suggests the occurrence of higher sea surface temperatures, was found to be far greater during the Medieval Warm Period than at any other time in the 2,000-year period studied. During the Current Warm Period, its relative abundance was lower than the 2,000-year mean.

Matul *et al*. (2007) studied the distributions of different species of siliceous microflora (diatoms), calcareous microfauna (foraminifers), and spore-pollen assemblages in sediment cores retrieved from 21 sites on the inner shelf of the southern and eastern Laptev Sea, starting from the Lena River delta and moving seaward between about 130 and 134°E and stretching from approximately 71 to 78°N. The cores were acquired by a Russian-French Expedition during the cruise of R/V *Yakov Smirnitsky* in 1991. The analysis indicated the existence of “the Medieval Warm Period, ~600–1100 years BP; the Little Ice Age, ~100–600 years BP, with the cooling maximum, ~150–450 years BP, and the ‘industrial’ warming during the last 100 years.” In addition, “judging from the increased diversity and abundance of the benthic foraminifers, the appearance of moderately thermophilic diatom species, and the presence of forest tundra (instead of tundra) pollen,” they conclude, “the Medieval warming exceeded the recent ‘industrial’ one.”

Using a well-established radiolarian-based transfer function, Fengming *et al*. (2008) developed a mean annual sea surface temperature (SST) history of the last 10,500 years based on data derived from the top 390 cm of a gravity core recovered from the western slope of the northern Okinawa Trough (29°13.93’N, 128°53’E) of the East China Sea. This record revealed that early in the Holocene, between 10,500 and 8,500 calendar years before present (cal. yr BP), mean annual SST gradually rose from ~23.5 to ~25.2°C, but it then declined abruptly to ~24.0°C at about 8,200 cal. yr BP. The middle portion of the Holocene that followed was relatively stable, with a mean SST of ~24.7°C, after which a dramatic cooling to ~23.6°C occurred at about 3,100 cal. yr BP that lasted until about 2,600 cal. yr BP, largely coincident with what is known as the “third Neoglaciation” of Europe.

This cold interval was followed by the Roman Warm Period (~2,600–1,700 cal. yr BP), when SSTs rose to ~24.8°C. Then came the Dark Ages Cold Period, when SSTs dropped to ~23.8°C, after which temperatures during the Medieval Warm Period (~1,250–750 cal. yr BP) returned to ~24.8°C, only to decline to ~24.2°C during the Little Ice Age (~600–300 cal. yr BP). Thereafter, it began to warm once again, but the warming was short-lived, with the temperature reversing course and falling slightly below the Little Ice Age minimum value of ~24.2°C at about AD 1950, where the SST history terminates.

This SST record from the East China Sea clearly reveals the millennial-scale cycling of climate seen in numerous paleoclimatic proxies throughout the world (see Figure 4.2.4.8.2.3), and it suggests the near-identical peak SSTs of the East China Sea during both the Medieval and Roman Warm Periods were

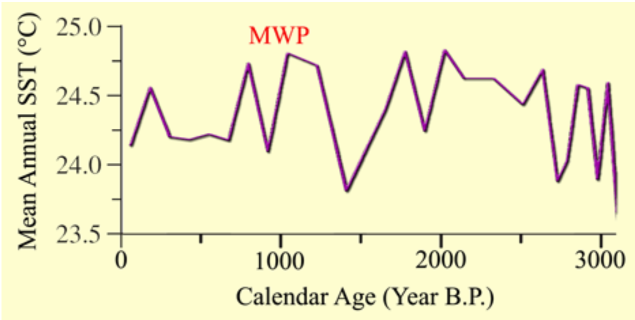

Figure 4.2.4.8.2.3. Sea surface temperature proxy derived from a gravity core recovered from the East China Sea. Adapted from Fengming, C., Tiegang, L., Lihua, Z., and Jun, Y. 2008. A Holocene paleotemperature record based on radiolaria from the northern Okinawa Trough (East China Sea). *Quaternary International* **183**: 115–122.

probably significantly greater than those of today, which likely have had insufficient time to reverse course and warm to such an elevated level from their lowest level of the past 1,300 years.

In reference to the claims of Jansen *et al*. (2007) and Mann *et al*. (2008) that Northern Hemisphere surface temperature reconstructions indicate "the late twentieth century was warmer than any other time during the past 500 years and possibly any time during the past 1,300 years," Oppo *et al*. (2009) state these temperature reconstructions may not be as representative of the planet as a whole as they are typically made out to be, because they "are based largely on terrestrial records from extra-tropical or high-elevation sites," whereas "global average surface temperature changes closely follow those of the global tropics, which are 75% ocean." The three researchers derived a "continuous sea surface temperature (SST) reconstruction from the IPWP [Indo-Pacific Warm Pool]," which they describe as "the largest reservoir of warm surface water on the Earth and the main source of heat for the global atmosphere." This temperature history, based on $\delta^{18}O$ and Mg/Ca data obtained from samples of the planktonic foraminifera *Globigerinoides ruber* found in two gravity cores, a nearby multi-core (all at 3°53'S, 119°27'E), and a piston core (at 5°12'S, 117°29'E) recovered from the Makassar Strait on the Sulawesi margin, spans the past two millennia (see Figure 4.2.4.8.2.4) and "overlaps the instrumental record, enabling both a direct comparison of proxy data to the instrumental record and an evaluation of past changes in the context of twentieth century trends."

They report the SST reconstruction "shows cooler temperatures between about AD 400 and AD 950 [the Dark Ages Cold Period] than during much of the so-called Medieval Warm Period (about AD 900–1300)." Of the latter period, they state, "reconstructed SSTs were warmest from AD 1000 to AD 1250," when "SSTs within error of modern SSTs occurred in the IPWP," as also was the case "during brief periods of the first millennium AD," during the Roman Warm Period. Thus a globally significant SST history, "enabling both a direct comparison of proxy data to the instrumental record and an evaluation of past

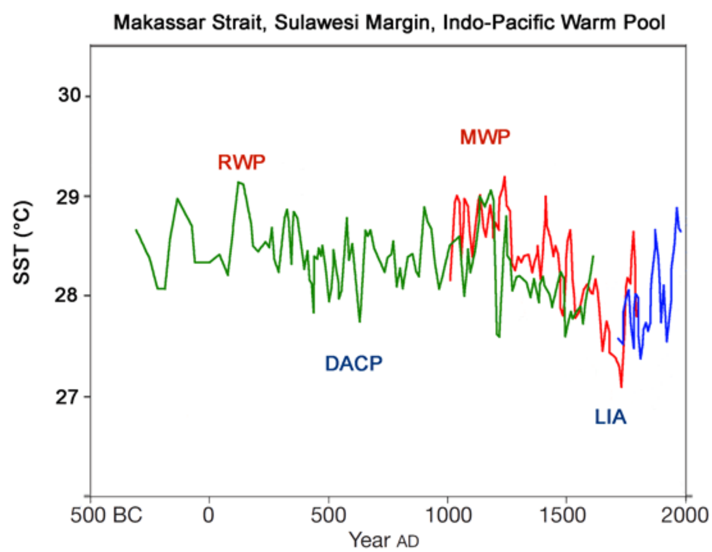

Figure 4.2.4.8.2.4. A 2,000-year temperature history, based on $\delta^{18}O$ and Mg/Ca data obtained from samples of a planktonic foraminifera found in ocean sediment cores recovered from the Makassar Strait on the Sulawesi margin of the Indo-Pacific Warm Pool. Adapted from Oppo, D.W., Rosenthal, Y., and Linsley, B.K. 2009. 2,000-year-long temperature and hydrology reconstructions from the Indo-Pacific warm pool. *Nature* **460**: 1113–1116.

changes in the context of twentieth century trends," shows substantial evidence that throughout portions of both the Roman and Medieval Warm Periods, SSTs in the Indo-Pacific Warm Pool were essentially equivalent to those of "the late twentieth century," once again indicating current air temperatures in this critically important region of the globe are not out of the ordinary.

Isono *et al.* (2009) studied three sediment cores retrieved off the coast of central Japan in the northwestern Pacific Ocean (36°02'N, 141°47'E) to generate a multi-decadal-resolution record of alkenone-derived sea surface temperature (SST) that covers the full expanse of the Holocene. This record, they write, "showed centennial and millennial variability with an amplitude of ~1°C throughout the entire Holocene," and they state, "spectral analysis for SST variation revealed a statistically significant peak with 1470-year periodicity." At the end of the record, Isono *et al.* report, "SST minima centered at ca. 0.3 ka and ca. 1.5 ka are correlated with the Little Ice Age and the Dark Ages Cold Period in Europe, respectively, whereas the SST maximum centered at ca. 1.0 ka is correlated with the Medieval Warm Period." From data presented in the authors' Figure 2, it can be estimated the MWP was about 1°C warmer than the Current Warm Period.

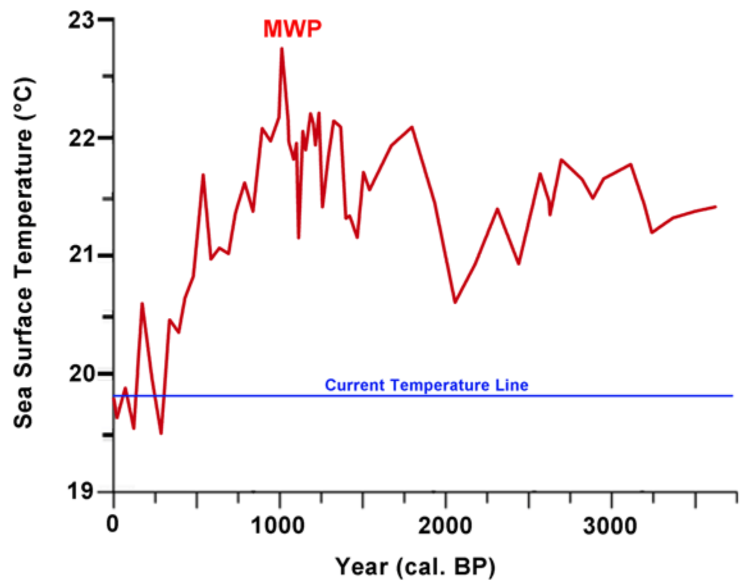

Figure 4.2.4.8.2.5. A 3,600-year proxy sea surface temperature record from the northern East China Sea. Adapted from Li, G.X., Sun, X.Y., Liu, Y., Bickert, T., and Ma, Y.Y. 2009. Sea surface temperature record from the north of the East China Sea since late Holocene. *Chinese Science Bulletin* **54**: 4507–4513.

Li *et al*. (2009) analyzed a sediment core extracted from the northern East China Sea (31.68°N, 125.81°E) in June 2006, employing the alkenone paleotemperature index $U^{k'}37$ together with the Muller *et al.* (1998) calibration equation to construct a sea surface temperature history of that region covering the past 3,600 years (Figure 4.2.4.8.2.5). They report "the highest temperature was 22.7°C which was recorded at 1.01 cal ka BP," about three-fifths of the way through the Medieval Warm Period. They also note cooling prevailed "from 0.85 cal. ka BP to present," with the latter point indicating a temperature of 19.78°C. We calculate, based on their work, the peak warmth of the MWP was 2.9°C greater than the mean warmth of the first decade of the twenty-first century, which is often characterized as the warmest decade of the instrumental period.

Richter *et al*. (2009) obtained high-resolution (22-year average) planktonic foraminiferal Mg/Ca and stable oxygen isotope ($\delta^{18}O$) data from a pair of sediment cores retrieved from the northeast Atlantic Ocean's Feni Drift, Rockall Trough region (55°39.02'N, 13°59.10'W and 55°39.10'N, 13°59.13'W), from which they derived late Holocene (0–2.4 ka BP) sea surface temperatures (SSTs). These data revealed "a general long-term cooling trend," but "superimposed on this overall trend" were "partly higher temperatures and salinities from 180 to 560 AD and 750–1160 AD," which the three researchers say "may be ascribed to the Roman and Medieval Warm Periods, respectively." The latter was followed by the Little Ice Age (LIA) and what they describe as the "post-LIA recovery and, possibly, (late) 20th century anthropogenic warming."

The twentieth century warming, they write, "concurs with distinct continental-scale warming, consistently reaching unprecedented maximum temperatures after ~1990 AD." Their use of the word "unprecedented" is a bit misleading, for they subsequently write, "the SST increase over the last three decades does not, or not 'yet', appear unusual compared to the entire 0–2.4 ka record," and "the warming trend over the second half of the 20th century has not yet reverted the late Holocene millennial-scale cooling." Their data clearly indicate the peak temperature of the Medieval Warm Period was approximately 2.2°C greater than the peak temperature of the late twentieth century, and the peak temperature of the Roman Warm Period was about 2.7°C greater than that of the late twentieth century.

That the warmest portions of the Roman and Medieval Warm Periods in the vicinity of the northeast Atlantic were so much warmer than the warmest of the Current Warm Period, and at times when the air's CO_2 content was much less than it is currently, strongly suggests the atmosphere's CO_2 concentration had little or no impact on the late-Holocene climatic history of that part of the planet. The three Dutch researchers state, "pervasive multidecadal- to centennial-scale variability throughout the sedimentary proxy records can be partly attributed to solar forcing and/or variable heat extraction from the surface ocean caused by shifts in the prevailing state of the North Atlantic Oscillation," as well as to "internal (unforced) fluctuations."

Sejrup *et al.* (2010) developed a 1,000-year-long proxy temperature record from two sediment cores extracted from the seabed of the eastern Norwegian Sea (~64°N, 3°E), "based on measurements of $\delta^{18}O$ in *Neogloboquadrina pachyderma*, a planktonic foraminifer that calcifies at relatively shallow depths within the Atlantic waters of the eastern Norwegian Sea during late summer." They found "the lowest isotope values (highest temperatures) of the last millennium are seen ~1100–1300 A.D., during the Medieval Climate Anomaly, and again after ~1950 A.D." By applying "relatively conservative isotopic estimates of temperature change" utilized by the authors of -0.25‰/°C, from the graphs of their data, it can be estimated the most extreme minimum $\delta^{18}O$ values of the 1100–1300 period yield temperatures at least 0.35°C warmer than those of the post-1950 period (see Figure 4.2.4.8.2.6).

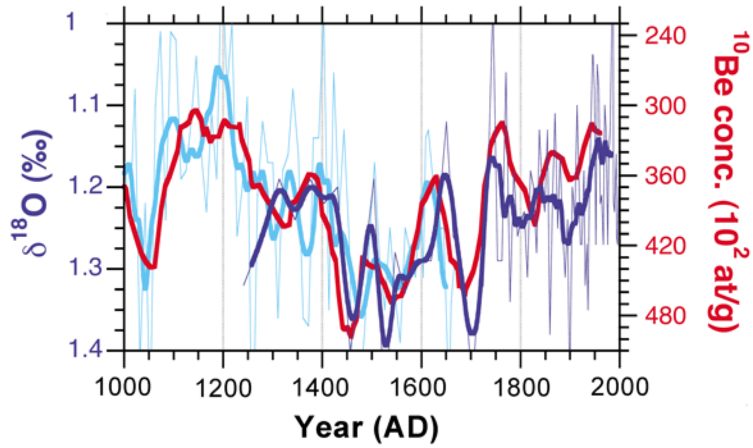

Figure 4.2.4.8.2.6. A 1,000-year proxy temperature record based on measurements of $\delta^{18}O$ in a planktonic foraminifer obtained from two sediment cores in the eastern Norwegian Sea. Adapted from Sejrup, H.P., Lehman, S.J., Haflidason, H., Noone, D., Muscheler, R., Berstad, I.M., and Andrews, J.T. 2010. Response of Norwegian Sea temperature to solar forcing since 1000 A.D. *Journal of Geophysical Research* **115**: 10.1029/2010JC006264.

Combining use of ^{210}Pb dates, identification of Icelandic tephras of known age, and wiggle matching of ^{14}C radiocarbon dates, Sejrup *et al.* (2011) established exceptionally accurate chronologies for two marine sediment cores raised from the same location on the Norwegian continental margin (63°45'44"N, 05°15'19"E) in 1998. They evaluated $\delta^{18}O$ values of the planktonic foram *Neoglobo-quadrina pachyderma* (dex), a parameter influenced by the temperature and salinity of the seawater in which the foram lives, over the 8,000-year period spanned by the retrieved cores. After noting the work of Berstad *et al.* (2003) suggests salinity should have a relatively small influence on the isotope values of *N. Pachy.* (dex) at the site of their study, they developed the $\delta^{18}O$ history depicted in Figure 4.2.4.8.2.7, which they use as a proxy for what they call "near surface water summer temperature." This history clearly shows the peak warmth of the Medieval Warm Period was significantly greater than the peak warmth of the Current Warm Period to date.

Ran *et al.* (2011) reconstructed summer sea surface temperature (SST) on the North Icelandic shelf for the period AD 940–2006, based on high-resolution and precisely dated diatom records and "a modern diatom-environmental dataset from around Iceland … established as a basis for quantitative reconstruction of palaeoceanographic conditions on the North Icelandic shelf (Jiang *et al.*, 2001, 2002)." The four researchers find the sea surface on the North Icelandic shelf "was not as warm during the last century as during the Medieval Warm Period (MWP)." They also state, "warm and stable conditions with relatively strong influence of the Irminger Current on the North Icelandic shelf are indicated during the interval AD 940–1300, corresponding in time to the MWP," and "a considerable cooling at ~AD 1300 indicates the transition to the Little Ice Age (LIA) with increased influence of Polar and Arctic water masses deriving from the East Greenland and East Icelandic currents." After that came "an extended cooling period between AD 1300 and 1910," followed by "a two-step warming during the last 100 years" that was "interrupted by three cool events around AD 1920, in the AD 1960s and in the late AD 1990s."

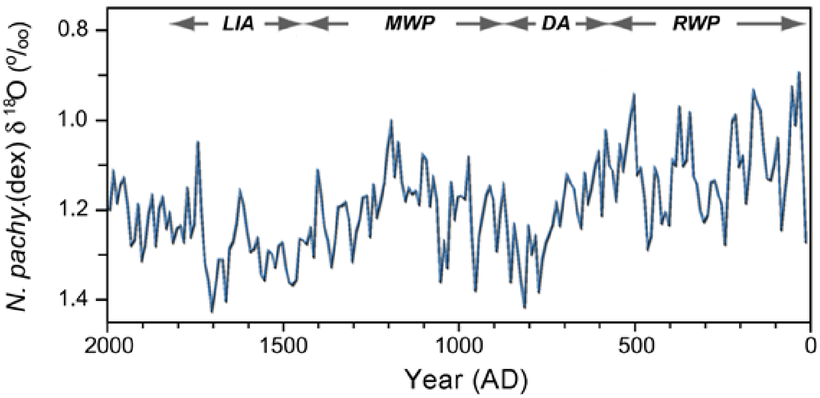

Figure 4.2.4.8.2.7. Proxy temperature reconstruction of *N. pachyderma* (dex) δ^{18}O vs. time. Adapted from Sejrup, H.P., Haflidason, H., and Andrews, J.T. 2011. A Holocene North Atlantic SST record and regional climate variability. *Quaternary Science Reviews* **30**: 3181–3195.

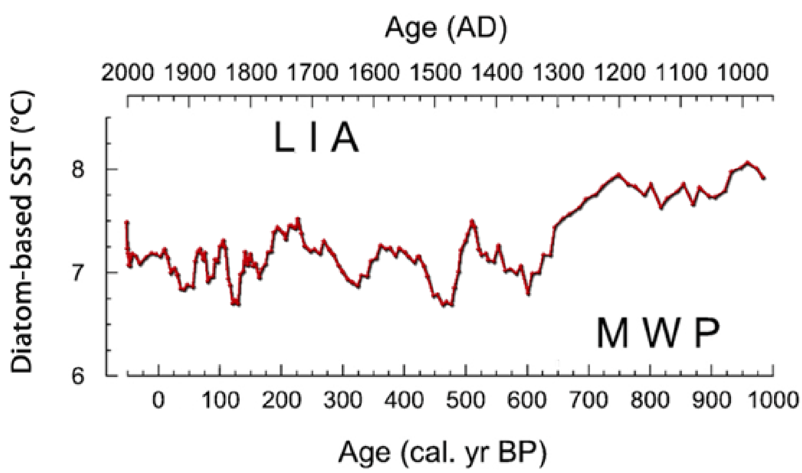

Figure 4.2.4.8.2.8. Reconstructed summer sea surface temperature (SST) on the North Icelandic shelf for the period AD 940–2006. Adapted from Ran, L., Jiang, H., Knudsen, K.L., and Eiriksson, J. 2011. Diatom-based reconstruction of palaeoceanographic changes on the North Icelandic shelf during the last millennium. *Palaeogeography, Palaeoclimatology, Palaeo-ecology* **302**: 109–119.

Ran *et al*. thus present another proxy record indicating the warmth of the more distant past clearly exceeded that of the recent past, with the peak temperature of the MWP exceeding that of the Current Warm Period at this location by about 0.6°C, as best as can be determined from the graphical representation of Ran *et al*.'s data presented in Figure 4.2.4.8.2.8. They conclude, "the data suggest that solar radiation may be one of the important forcing mechanisms behind the palae-oceanographic changes."

Saenger *et al*. (2011) analyzed seabed sediment sub-cores taken from a giant gravity core (59GGC) and a multicore (MC22) separated from each other by 22 km along the Carolina Slope of the western North Atlantic Ocean near the southern flank of the Gulf Stream at 32.977°N, 76.316°W and 32.784°N, 76.276°W, respectively, developed two sets of 2,000-year sea surface temperature (SST) histories based on Mg/Ca ratios of the shells of the planktic foraminifera *Globi-gerinoides ruber*, using two Mg/Ca-SST calibrations: that of Anand *et al*. (2003) for both cores and that of Arbuszewski *et al*. (2010) for the 59GGC core only.

Using the calibration of Anand *et al*. (2003), the peak warmth of the MWP is seen to have been about 0.1°C less than that of the CWP based on both the 59GGC and MC22 core data. When using the calibration of Arbuszewski *et al*. (2010), the peak warmth of the MWP is seen to have been about 0.7°C greater than that of the CWP based on the data from the 59GGC core. Thus Saenger *et al*.'s study suggests the peak warmth of the MWP was 0.1°C less than that of the CWP, and it also suggests the peak warmth of the MWP was 0.7°C greater than that of the CWP at the 59GGC site, with the MWP of both sites falling in the range of about AD 700–1300. Whichever calibration creates the more accurate record, it is clear temperatures in the region are hardly unusual or unnatural.

Copard *et al*. (2012) extracted the rare earth element *neodymium* (Nd) from pristine aragonite fragments of fossil deep-sea corals of the species *Lophelia pertusa* taken by gravity core from the southwestern flank of Rockall Trough in the Northeast Atlantic Ocean (55°31.17'–55°32' N, 15°39.08'–15°40'W). They calcu-lated iso-topic composition (εNd) according to the relationship εNd =([(^{143}Nd/^{144}Nd)sample/0.512638]-1) x 10,000, as per Jacobsen and Wasserberg (1980). Copard *et al*. state,

"the warm Medieval Climate Anomaly (1,000–1250 AD) was characterized by low εNd values (-13.9 to -14.5) ... while the Little Ice Age (around 1350–1850 AD) was marked by higher εNd values." After the end of the LIA, εNd once again declines, but according to the author's Figure 5d, it never quite reaches the -13.9 value that defines the boundary condition (εNd = -13.9) of the beginning and end of the MWP. Because the εNd value of modern seawater recirculating in the northern North Atlantic at surface and intermediate depths is only -13.1, it can be cautiously concluded ocean temperatures during the Current Warm Period have not eclipsed those experienced during Medieval times.

Wu *et al*. (2012) write, "one of the key questions in the reconstruction of late Holocene climate is whether or not the 20th-century warming is unusual over the past two millennia," noting "a clear answer to this question is crucial for the assessment of the relative contribution of human activities and natural processes to the observed warming." They developed a bi-decadal-resolution record of sea surface temperature (SST) in the Southern Okinawa Trough covering the past 2,700 years by analyzing tetraether lipids of planktonic archaea in the ODP Hole 1202B (24°48'N, 122°30'E), which they describe as "a site under the strong influence of the Kuroshio Current and East Asian monsoon."

The five Chinese researchers report finding SST anomalies that "generally coincided with previously reported late Holocene climate events, including the Roman Warm Period [120 BC–AD 400], Sui-Tang Dynasty Warm Period [AD 550–790], Medieval Warm Period [AD 900–1300], Current Warm Period [AD 1850–present], Dark Age Cold Period [AD 400–550] and Little Ice Age [AD 1300–1850]." They note, "despite an increase since AD 1850, the mean SST in the 20th century is still within the range of natural variability during the past 2700 years." In addition, they note climate records from East China (Ge *et al*., 2004), the North Icelandic Shelf (Patterson *et al*., 2010), and Greenland (Kobashi *et al*., 2011) also exhibit "centennial-scale warm periods during the first millennia AD, comparable to or even warmer than mean 20th-century conditions."

Moros *et al*. (2012) inferred late-Holocene trends and variability of the East Greenland Current's influence on the Sub-Arctic Front, based on new oxygen isotope data of three planktonic foraminiferal species, Mg/Ca-derived sea-surface temperature data, alkenone biomarker paleothermometry, coccolith abundance, species counts, and diatom census data derived from a sediment core extracted from Reykjanes Ridge at 58°56.327'N, 30°24.590'W in the North Atlantic Ocean. They found "increasingly colder millennial-scale cooling events" centered on 5.6, 3.8, 2.7, 1.3, and 0.3 ka, the latter and coldest of which was the Little Ice Age. Between the third and fourth of these cold events was the Roman Warm Period, which they describe as the warmest period of the late Holocene.

Climate change is real. In fact, it's the *norm*. And in the several oceanic studies briefly reviewed above, as well as studies pertaining to the terrestrial surface of the planet reported on elsewhere in this Section 4.2, Earth's climate has been recognized as having shifted over the past century or so from the coldest period of the current interglacial to a significantly warmer state, but one that appears not yet to have achieved the level of warmth characteristic of the prior Medieval Warm Period or the earlier Roman Warm Period. Since none of these warming periods was driven by increases in the air's CO_2 concentration, there is no compelling reason to conclude—especially with the level of certainty expressed by the IPCC—that the twentieth century warming of the globe was driven by concurrent anthropogenic CO_2 emissions.

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4.2.4.8.3 Past Century

Dippner and Ottersen (2001) produced a twentieth century (1900–1995) history of mean sea water temperature from the surface to a depth of 200 meters for the Kola Section of the Barents Sea, which stretches from 70°30’N to 72°30’N along the 33°30’ E meridian. The record they developed indicates the mean temperature of the upper 200 meters of water rose by approximately 1°C from 1900 to 1940, after which it declined until about 1980 and then rose to the end of the record. The latter increase was not great enough to bring water temperatures back to the highs they experienced in the 1940s and early 1950s, and a linear regression from 1940 onward (or even 1930 onward) would produce a negative slope indicative of an overall cooling trend over the final 55 (or 65) years of the record.

Bratcher and Giese (2002) note the general trend of global surface air temperature was one of warming, but they caution there was “considerable variation in the upward trend,” and “how much of this variability is attributable to natural variations and how much is due to anthropogenic contributions to atmospheric greenhouse gases has not yet been resolved.” They add, “the possibility exists that some portion of the recent increase in global surface air temperature is part of a naturally oscillating system.” Hence, they explore “the recent record of Southern Hemisphere subsurface [ocean water] temperature anomalies and whether they may be an indicator of future global surface air temperature trends.”

The two researchers found “low frequency changes of tropical Pacific temperature lead global surface air temperature changes by about four years,” and "anomalies of tropical Pacific surface temperature are in turn preceded by subsurface temperature anomalies in the southern tropical Pacific by approximately seven years." In addition, they document a distinct cooling of the southern tropical Pacific over the prior eight years, leading them to conclude "the warming trend in global surface air temperature observed since the late 1970s may soon weaken." They proved correct, as the previous upward trend in the globe's mean surface air temperature—from the time of their writing—not only weakened but reversed course and began to trend downward.

Chavez *et al*. (2003) analyzed "physical and biological fluctuations with periods of about 50 years that are particularly prominent in the Pacific Ocean," including air and ocean temperatures, atmospheric CO_2 concentration, landings of anchovies and sardines, and the productivity of coastal and open ocean ecosystems. They found "sardine and anchovy fluctuations are associated with large-scale changes in ocean temperatures: for 25 years, the Pacific is warmer than average (the warm, sardine regime) and then switches to cooler than average for the next 25 years (the cool, anchovy regime)." They also found "instrumental data provide evidence for two full cycles: cool phases from about 1900 to 1925 and 1950 to 1975 and warm phases from about 1925 to 1950 and 1975 to the mid-1990s." These warm and cool regimes, which they respectively called El Viejo ("the old man") and La Vieja ("the old woman"), were manifest in myriad similar-scale biological fluctuations that may be even better indicators of climate change than climate data themselves, in the researchers' estimation.

The findings of this unique study have many ramifications, especially the challenge they present for the detection of CO_2-induced global warming. Chavez *et al*. note, for example, data used in climate change projections are "strongly influenced by multidecadal variability of the sort described here, creating an interpretive problem." They conclude "these large-scale, naturally occurring variations must be taken into account when considering human-induced climate change." The warming of the late 1970s to late 1990s, which returned much of the world to the level of warmth experienced during the 1930s and 1940s, has ended and reversed course. Chavez *et al*. cite evidence that indicates a change from El Viejo to La Vieja conditions was already in progress at the time of their writing.

Breaker (2005) performed statistical analyses on a daily sea-surface temperature (SST) record from the Hopkins Marine Station in Pacific Grove, California (USA), located at the southern end of Monterey Bay, for the period 1920–2001, to identify and estimate the relative importance of atmospheric and oceanic processes that contribute to the variability in the SST record on seasonal to interdecadal time scales. Based on monthly averages, Breaker found approximately 44 percent of the variability in the Pacific Grove data came from the annual cycle, 18 percent from El Niño warming episodes, 6 percent from the Pacific Decadal Oscillation (PDO), 4 percent from the long-term trend, and 3 percent from the semiannual cycle. Linear analysis of the 82-year record revealed a statistically significant SST increase of 0.01°C per year, and this trend is similar to the findings of other researchers who have attributed the trend to CO_2-induced global warming. Further analyses by Breaker suggest this attribution may have been premature.

Breaker discovered two major regime shifts associated with the PDO over the course of the record, one at about 1930 and one in 1976, which could explain most of the 82-year warming. Prior to the regime shift around 1930, for example, the waters of Monterey Bay were, in Breaker's words, "much colder than at any time since then." And if one computes the linear SST trend subsequent to this regime shift, which Breaker did, the resulting 72-year trend is a non-statistically significant +0.0042°C. Breaker concludes, "although the long-term increase in SST at Pacific Grove appears to be consistent with global warming, the integrated anomaly suggests that temperature increases in Monterey Bay have occurred rather abruptly and thus it becomes more difficult to invoke the global warming scenario."

Breaker's study clearly demonstrates decadal-scale regime shifts can dwarf any potential "fingerprint" of CO_2-induced global warming that might be present in twentieth century SST datasets. Also, it is clear the regime shift around 1930 was not the product of anthropogenic-induced global warming, because so little of the current burden of anthropogenic greenhouse gases had been released to the atmosphere prior to that time compared to what was subsequently released.

Hobson *et al*. (2008) used SST data from the International Comprehensive Ocean-Atmosphere Data Set to calculate, in annual time steps, the mean August–September positions of the 12, 15, and 18°C isotherms in the North Atlantic Ocean from 1854 to 2005 at 2-degree longitudinal intervals. They found the three isotherms "have tended to move northwards during two distinct periods: in the 1930s–1940s and then again at the end of the 20th century"; "the chances of this occurring randomly are negligible"; the 15°C isotherm "reached a maximum latitude of 52.0°N in 1932, and a latitude of 51.7°N in 2005, a difference of approximately 33 km"; and "of the 10 most extreme years, 4 have occurred in the 1992–2005 warm era and 3 have occurred in the 1926-1939 era."

The UK and Australian researchers conclude, "current 'warm era conditions' do not eclipse prior 'warm' conditions during the instrumental record," indicating the period of most significant greenhouse gas buildup over the past century (1930 and onward) brought little or no net increase in SSTs throughout this large sector of the North Atlantic Ocean.

DeCastro *et al*. (2009) employed two sea surface temperature (SST) datasets to reconstruct the SST history of the Bay of Biscay for the period 1854–2007: an extended reconstructed SST history obtained from NOAA/OAR/ESRL PSD of Boulder, Colorado, USA, for the period 1854–1997; and weekly mean SST data obtained from nighttime measurements made by Advanced Very-High Resolution Radiometers onboard NOAA satellites for the period 1985–2006. They did so, they write, "to put the intensity of the present warming trend within the context of the last two centuries."

The authors report, "two consecutive warming-cooling cycles were detected during the period 1854–2007: cooling from 1867 to 1910 (-0.14°C per decade); warming from 1910 to 1945 (0.17°C per decade); cooling from 1945 to 1974 (-0.10°C per decade); and warming from 1974 to 2007 (0.22°C per decade)." The four Spanish scientists state, "the present warming period (1974–2007) is on the same order of magnitude although slightly more intense than the one observed from 1910 to 1945." They conclude, "this fact does not permit elucidating the possible anthropogenic influence on the present day warming, which still remains an open question." This conclusion, they write, "is consistent with the analysis carried out by Hobson *et al*. (2008) for the North Atlantic," who also conclude "current 'warm era conditions' do not eclipse prior 'warm' conditions during the instrumental record." With respect to sea surface temperature, they observe, "the North Atlantic remains within the envelope of previous recorded conditions."

Halfar *et al*. (2011) state, "mid- and high-latitude crustose coralline algae are an emerging extra-tropical marine climate archive," as was demonstrated during a field calibration study (Halfar *et al*., 2008), because "they are amongst the longest-lived shallow marine organisms (Frantz *et al*., 2005)," and "they show constant growth over their lifespan and are not subject to an ontogenetic growth trend with skeletal age." Using "a regional network of specimens of the coralline alga *Clathromorphum compactum* spanning portions of the Labrador Current inshore branch from the Gulf of St. Lawrence to both latitudinal extremes of the eastern Newfoundland shelf," the authors generated "a 115-year-long growth-increment-width based record of subarctic northwest Atlantic surface temperatures."

The new temperature reconstruction reveals "the well-documented regime shift and warming in the northwestern Atlantic during the 1990s." The eight researchers further report, "large positive changes in algal growth anomalies were also present in the 1920s and 1930s, indicating the impact of a concurrent large-scale regime shift throughout the North Atlantic was more strongly felt in the subarctic Northwestern Atlantic than previously thought." They state this regime shift "may have even exceeded the 1990s event with respect to the magnitude of the warming," as "has recently been suggested for the central and eastern North Atlantic," citing Drinkwater (2006).

This study adds to a large body of evidence documenting warmer temperatures in the 1920s and 1930s than in the late 1990s/early 2000s, an observation at odds with the IPCC's claims the warming of the past two decades is unprecedented over the past millennium or more. The air's CO_2 concentration in the 1920s and 1930s was roughly 300–305 ppm; today's atmosphereic CO_2 concentration is about 400 ppm, some 30 percent greater than during those warmer times.

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4.2.8.4.4 Past Few Decades

What do ocean temperatures tell us about the theory of CO_2-induced global warming? This section considers what can and cannot be inferred from studies of the past few decades.

In a *Science* news story highlighting the work of Levitus *et al*. (2000), Richard Kerr's title all but announced the finding of climatology's Holy Grail: "Globe's 'Missing Warming' Found in the Ocean." Was that really the case? Before considering this question, it is instructive to note Kerr clearly acknowledges much of the warming that had long been predicted to occur as a consequence of the historical rise in the atmosphere's CO_2 concentration had indeed been missing. That is to say, his choice of words was admissive of the fact that Earth's atmosphere had not warmed by the amount that had long been predicted.

So how much of the missing warming was supposedly found? In a detailed analysis of a vast array of oceanic temperatures spanning the globe and extending from the surface down to a depth of 3,000 meters, Levitus *et al*. detected an incredibly small 0.06°C temperature increase between the mid-1950s and mid-1990s. Because the world's oceans have a combined mass 2,500 times greater than that of the atmosphere, this figure, as small as it seems, was truly significant. But was it correct?

Although their data extended back in time several years beyond the point at which they specified the warming to begin, Levitus *et al*. computed the linear trend in temperature between the lowest valley of their oscillating time series and its highest peak, ensuring they would obtain the largest warming possible. Over a moderately longer time period, global ocean warming would have been computed to be much less than what Levitus *et al*. reported, and the extended record would make the rate of warming smaller still. Nevertheless, NASA's James Hansen was quoted by Kerr as saying the new ocean-warming data "imply that climate sensitivity is not at the low end of the spectrum" that had typically been considered plausible.

But scientists were not interested only in the magnitude of the warming; they also wondered about cause. Climate modeler Jerry Mahlman, for example, stated, according to Kerr, that the study of Levitus *et al*. "adds credibility to the belief that most of the warming in the 20th century is anthropogenic." Yet Levitus *et al*. had clearly stated in their *Science* paper, "we cannot partition the observed warming to an anthropogenic component or a component associated with natural variability," which brings us to the subject of climate sensitivity. To calculate such a parameter one must have values for both a climate forcing and a climate response. If one cannot identify the source of the forcing, much less its magnitude, it is clearly impossible to calculate a sensitivity.

Levitus *et al*. (2001) and Barnett *et al*. (2001) added to the documentation of the modest warming of the planet's deep oceans. With respect to this accomplishment, Lindzen (2002) wrote, "the fact that models forced by increasing CO_2 and tuned by nominal inclusion of aerosol effects to simulate the global mean temperature record for the past century roughly matched the observed deep ocean record was taken as evidence of the correctness of the models and of the anthropogenic origin of the deep ocean warming." However, he took strong exception to this conclusion.

Assuming the deep-ocean temperature measurements and their analysis were correct, Lindzen used a coupled climate model (an energy balance model with a mixed layer diffusive ocean) "to examine whether deep ocean temperature behavior from 1950 to 2000 actually distinguishes between models of radically different sensitivity to doubled

CO_2." This revealed the warming of the deep oceans, in Lindzen's words, "is largely independent of model sensitivity," which led him to conclude "the behavior of deep ocean temperatures is not a test of model sensitivity, but rather a consequence of having the correct global mean surface temperature time history." He notes, "we are dealing with observed surface warming that has been going on for over a century" and "the oceanic temperature change over the period 1950–2000 reflects earlier temperature changes at the surface."

Further to this point, it should be noted according to the data of Esper *et al*. (2002), the Earth began to warm in the early 1800s, and the warming of the twentieth century, according to Briffa and Osborn (2002), was "a continuation of a trend that began at the start of the 19th century." Earth had completed the bulk of its post-Little Ice Age temperature rebound well before much of the Industrial Revolution's CO_2 emissions entered the atmosphere; i.e., by about 1930. As a result, the modest rise in deep-water temperatures over the past half-century or so tells us nothing about the sensitivity of Earth's climate to atmospheric CO_2 enrichment, nor does it link the warming to anthropogenic CO_2 emissions.

He *et al*. (2002) used stable oxygen isotope data acquired from a core of *Porites lutea* coral on the east of Hainan Island in the South China Sea to develop a 56-year (1943–1998) history of sea surface temperature in that region. They report the sea surface temperature in the 1940s "was warmer than that in the 1980s–1990s," by as much as 1.5°C.

Motivated by reports of "extraordinary change in the Arctic Ocean observed in recent decades," Polyakov *et al*. (2003) began their study by referencing the work of Carmack *et al*. (1995) and Woodgate *et al*. (2001), who had reported evidence of positive Atlantic Layer Core Temperature (ALCT) anomalies of up to 1°C in the 150- to 800-meter depth interval. Polyakov *et al*. note, however, an evaluation of the significance of these anomalies "requires an understanding of the underlying long-term variability" of the pertinent measurements.

The data employed by Polyakov *et al*. included temperature and salinity measurements from Russian winter surveys of the central Arctic Ocean carried out over the period 1973–1979, derived from 1034 oceanographic stations and constituting "the most complete set of arctic observations." In addition, they utilized 40 years of summer and winter observations from the Laptev Sea. Based on these comprehensive measurements, they determined new statistical estimates of long-term variability in both ALCT and sea-surface salinity (SSS). This work demonstrates the standard dataset that had been used to suggest the existence of the apparent 1°C temperature anomalies of the 1990s "considerably underestimates variability," as the observed ALCT anomalies in the late 1970s were fully as great as those of the 1990s.

Polyakov *et al*. state their new statistical analyses placed "strong constraints on our ability to define long-term means," as well as the magnitudes of ALCT and SSS anomalies computed using synoptic measurements from the 1990s referenced to means from earlier climatologies. Consequently, what some had described as "the extraordinary change in the Arctic Ocean observed in recent decades" turned out to be not extraordinary at all; it was merely a reappearance of conditions that had prevailed a few years earlier.

Freeland *et al*. (2003) analyzed water temperature and salinity measurements made at a number of depths over a period of several years along two lines emanating from central Oregon and Vancouver Island westward into the Pacific Ocean. The data indicate subsurface waters in an approximate 100-meter-thick layer located between 30 and 150 meters depth off central Oregon were, in the words of the researchers, "unexpectedly cool in July 2002." Mid-depth temperatures over the outer continental shelf and upper slope were more than 0.5°C colder than the historical summer average calculated by Smith *et al*. (2001) for the period 1961–2000, which Freeland *et al*. state, "might be cooler than a longer-term mean because the 1961–71 decade coincided with a cool phase of the Pacific Decadal Oscillation (Mantua *et al*., 1997)." At the most offshore station, they report "the upper halocline [was] >1°C colder than normal and about 0.5°C colder than any prior observation." In addition to being substantially cooler, the anomalous water was also much fresher, and the combined effects of these two phenomena made the water less "spicy," as Freeland *et al*. describe it—so much so that they refer to the intensity of the spiciness anomaly as "remarkable."

Along the line that runs from the mouth of Juan de Fuca Strait to Station Papa at 50°N, 145°W in the Gulf of Alaska, which was sampled regularly between 1959 and 1981 and irregularly thereafter, similarly low spiciness was observed, which in the researchers' opinion is the same feature as detected off the coast of central Oregon. They report "conditions in June 2002 [were] well outside the bounds of all previous experience," and "in summer 2001 the spiciness of this layer was already at the lower bound of previous experience."

Freeland *et al*. conclude their data implies "the waters off Vancouver Island and Oregon in July 2002 were displaced about 500 km south of their normal summer position." Was this observation an indication the Pacific Ocean was beginning to experience a shift from what Chavez *et al*. (2003) called a "warm, sardine regime" to a "cool, anchovy regime"? It is tempting to suggest it was. Freeland *et al*. cautioned against jumping to such a conclusion, saying there were no obvious signals of such a regime shift in several standard climate indices and that without evidence of a large-scale climate perturbation, the spiciness anomaly might have been simply anomalous. Consequently, although the pattern of Pacific Ocean regime shifts documented by Chavez *et al*. suggest a change from warmer to cooler conditions might have been imminent, there was not at that time sufficient climatic evidence to conclude such a shift was occurring.

In reference to the 1976–1977 regime shift in the Pacific, Chavez *et al*. note, "it took well over a decade to determine that a regime shift had occurred in the mid-1970s" and hence, "a regime or climate shift may even be best determined by monitoring marine organisms rather than climate," as suggested by Hare and Mantua (2000). Chavez *et al.* cite several studies that appeared to provide such evidence, including "a dramatic increase in ocean chlorophyll off California," which would seem a logical response to what Freeland *et al*. described as "an invasion of nutrient-rich Subarctic waters." Other pertinent evidence cited by Chavez *et al*. includes "dramatic increases in baitfish (including northern anchovy) and salmon abundance off Oregon and Washington" and "increases in zooplankton abundance and changes in community structure from California to Oregon and British Columbia, with dramatic increases in northern or cooler species."

McPhaden and Zhang (2004) report between the mid-1970s and mid-1990s sea surface temperatures in the eastern and central equatorial Pacific Ocean rose by about 0.7°C in response to a slowdown of the shallow meridional overturning circulation, and some scientists had suggested these phenomena were the result of greenhouse gas forcing. They also note the existence of evidence for a late 1990s "regime shift" in the North Pacific (Chavez *et al*., 2003; Peterson and Schwing, 2003) that could temper or even refute the other interpretation of the data.

Since year-to-year fluctuations associated with El Niño and La Niña conditions can greatly influence Earth's climate system, the two researchers compared mean conditions in the eastern and central equatorial Pacific Ocean for the six-year period July 1992–June 1998 with the more recent five-year period July 1998–June 2003, both of which intervals spanned at least one complete ENSO warm and cold phase cycle. In addition to sea surface temperatures, their investigation utilized hydrographic and wind data spanning the period 1992–2003 to calculate geostrophic meridional volume transports in the upper pycnocline of the tropical Pacific.

These data and analyses indicated "the shallow meridianal overturning circulation in the tropical Pacific Ocean has rebounded since 1998, after 25 years of significantly weaker flow." McPhaden and Zhang determined it had "recently rebounded to levels almost as high as in the 1970s." Likewise, the area-averaged sea surface temperature in the eastern and central equatorial Pacific Ocean concurrently dropped approximately 0.6°C to almost equal the low of the mid-1970s and match the low of the previous regime in the mid-1950s.

McPhaden and Zhang conclude the "precise magnitude of anthropogenic influences [on tropical Pacific sea surface temperatures] will be difficult to extract with confidence from the instrumental record given the rapidity with which observed warming trends can be reversed by natural variations."

Lyman *et al*. (2006) note, "with over 1000 times the heat capacity of the atmosphere, the World Ocean is the largest repository for changes in global heat content," and "monitoring ocean heat content is therefore fundamental to detecting and understanding changes in the Earth's heat balance." Consequently, "using a broad array of in situ temperature data from expendable bathythermographs, ship board conductivity-temperature-depth sensors, moored buoy thermistor records, and autonomous profiling conductivity-temperature-depth floats," they estimated the global integral of ocean heat content anomaly of the upper 750 meters from the start of 1993 through the end of 2005.

This undertaking revealed that from 1993 to 2003 the heat content of the upper 750 meters of the world ocean increased by 8.1 (±1.4) x 10^{22} J, but "this increase was followed by a decrease of 3.2 (±1.1) x 10^{22} J between 2003 and 2005." This decrease, they write, "represents a substantial loss of heat over a 2-year period, amounting to about one fifth of the long-term upper-ocean heat gain between 1955 and 2003 reported by Levitus *et al*. (2005)." They also found "the maximum cooling occurs at about 400 m," and "the cooling signal is still strong at 750 m and appears to extend deeper." They report preliminary estimates "show that additional cooling occurred between depths of 750 and 1400 m." As for the source of the cooling, they say it "could be the result of a net loss of heat from the Earth to space."

Lyman *et al*. note the physical causes of the type of variability they discovered "are not yet well understood," and "this variability is not adequately simulated in the current generation of coupled climate models used to study the impact of anthropogenic influences on climate," which "may complicate detection and attribution of human-induced climate influences." This statement suggests there has not yet been an adequate demonstration of human-induced influences on world ocean temperatures. It also would appear there currently is little hope of finding such a connection in subsets of world ocean data any time soon, for "the relatively small magnitude of the globally averaged signal is dwarfed by much larger regional variations in ocean heat content anomaly." Whereas "the recent decrease in heat content amounts to an average cooling rate of -1.0 ± 0.3 Wm^{-2} (of the Earth's total surface area) from 2003 to 2005," regional variations "sometimes exceed the equivalent of a local air-sea heat flux anomaly of 50 Wm^{-2} applied continuously over 2 years."

Noting the global-scale study of the world's oceans conducted by Levitus *et al*. (2005) suggested a significant increase in the heat content of the upper 3-km layer between 1957 and 1997, Gouretski and Koltermann (2007) contend Levitus *et al*. did not take into account "possible temperature biases associated with differing instrumentation." The large database employed by Levitus *et al*. was derived from five types of instruments—mechanical and expandable bathythermographs (MBTs and XBTs), hydrographic bottles (Nansen and Rosette), conductivity-temperature-depth (CTD) instruments, and profiling floats—and they analyzed temperature offsets among them and applied their findings to temporal trends in the degree of each type of instrument's usage over the period in question.

Gouretski and Koltermann note XBT data comprised the largest proportion of the total database, and "with XBT temperatures being positively biased by 0.2-0.4°C on average," this bias resulted in "a significant World Ocean warming artifact when time periods before and after introduction of XBTs [were] compared." When Gouretski and Koltermann used the bias-correction techniques they developed, the ocean heat content increase since the 1950s was reduced by a factor of 0.62. They write, "such corrections if applied would correspondingly reduce the estimate of the ocean warming in Levitus *et al*. (2005) calculations." Gouretski and Koltermann's work indicates the warming of the global ocean over the last half of the twentieth century as calculated by Levitus *et al*. (2005) was seriously overestimated.

Harrison and Carson (2007) sorted individual temperature observations in the World Ocean Database 2001 into 1°x1° and 2°x2 ° bins, after which, working only with bins having at least five observations per decade for four of the five decades since 1950, they calculated 51-year temperature trends for depths of 100, 300, and 500 meters, as well as sequential 20-year trends—i.e., 1950-1970, 1955–1975, 1960–1980, and 1980–2000—for the same depths. Based on the results, which were statistically significant at the 90% confidence level, they determined the upper ocean "is replete with variability in space and time, and multi-decadal variability is quite energetic almost everywhere." They found 95 percent of the 2°x2° regions they studied "had both warming and cooling trends over sequential 20-year periods," and "the 51-year trends are determined in a number of regions by large trends over 20- to 25-year sub-periods." They conclude, "trends based on records of one or two decades in length are unlikely to represent accurately longer-term trends," and, therefore, "it is unwise to attempt to infer long-term trends based on data from only one or two decades." In addition, they note, "the magnitude of the 20-year trend variability is great enough to call into question how well even the statistically significant 51-year trends ... represent longer-term trends."

Carson and Harrison (2008) derived and analyzed ocean temperature trends over the period 1955–2003 at depths ranging from 50 to 1,000 meters to "test the sensitivity of trends to various data processing methods." They used the *World Ocean Database 2005* (Boyer *et al*., 2006), employed the analytical approach of Harrison and Carson (2007), and compared their results with those of Levitus *et al*. (2005). They find, "most of the ocean does not have significant 50-year trends at the 90% confidence level (CL)." They state, "only 30% of the ocean at 50 meters has 90% CL trends, and the percentage decreases significantly with increasing depth." In comparison with prior calculated trends, they also report the results "can differ substantially, even in the areas with statistically significant trends," noting, "trends based on the more interpolated analyses," such as those of Levitus *et al*. (2005), "show more warming." Thus the two researchers conclude, "ocean heat content integrals and integral trends may be substantially more uncertain than has yet been acknowledged."

In concluding this summary of the global ocean's thermal behavior over the past few decades, we discuss two papers that deal more with processes than with history. The first of these papers is that of Kleypas *et al*. (2008), who looked for evidence of an ocean thermostat by analyzing patterns of sea surface temperature (SST) increases in the tropics over the past five decades. They focused their attention on the western Pacific warm pool (WPWP), because, they write, "this is a region where maximum SSTs are thought to be limited by negative feedbacks," as described in the writings of Reginald Newell (1979), whom they cite and who in collaboration with Thomas Dopplick demonstrated, nearly three decades ago, that the degree of CO_2-induced global warming predicted by the climate models of that day was far greater (and is greater still today) than what is allowed by the real world (Newell and Dopplick, 1979), as further described in the historical narrative of Idso (1982).

Kleypas *et al*. say their analysis indicates "the warmest parts of the WPWP have warmed less than elsewhere in the tropical oceans," which "supports the existence of thermostat mechanisms that act to depress warming beyond certain temperature thresholds." In addition, they report "coral reefs within or near the WPWP have had fewer reported bleaching events relative to reefs in other regions," which is also indicative of the existence of an upper-limiting temperature above which SSTs typically do not rise, presumably because the oceanic thermostat kicks in when they approach 30°C in the region the three researchers describe as "the center of coral reef biodiversity."

These findings support the thesis put forward years ago by both Newell and Dopplick (1979) and Idso (1980, 1982, 1989): that rather than Earth possessing some thermal "tipping point" above which global warming dramatically accelerates, the planet's climatic system does just the opposite and greatly attenuates warming above a certain level.

Shaviv (2008) begins by noting "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references, many more of which can be found in Chapter 3 of this volume. Nevertheless, it is difficult for some to accept the logical derivative of this fact—that solar variations are driving major climate changes—their prime objection being that measured or reconstructed variations in total solar irradiance seem far too small to be able to produce the observed climatic changes.

One potential way to resolve this dilemma would be to discover some amplification mechanism, but most attempts have been fraught with difficulty and met with much criticism. Shaviv, however, makes a good case for at least the existence of such an amplifier, and he points us in the direction of a sensible candidate to fill this role.

Shaviv used "the oceans as a calorimeter to measure the radiative forcing variations associated with the solar cycle" via "the study of three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations," each of which can be used, in his words, "to consistently derive the same oceanic heat flux."

Shaviv demonstrates "there are large variations in the oceanic heat content together with the 11-year solar cycle." In addition, he reports the three independent datasets "consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance," thus "implying," as he describes it, "the necessary existence of an amplification mechanism, although without pointing to which one."

Shaviv nonetheless acknowledges his affinity for the solar-wind modulated cosmic ray flux (CRF) hypothesis suggested by Ney (1959), discussed by Dickenson (1975), and championed by Svensmark (1998). Based on "correlations between CRF variations and cloud cover, correlations between non-solar CRF variations and temperature over geological timescales, as well as experimental results showing that the formation of small condensation nuclei could be bottlenecked by the number density of atmospheric ions," this concept, according to Shaviv, "predicts the correct radiation imbalance observed in the cloud cover variations" needed to produce the magnitude of the net heat flux into the oceans associated with the 11-year solar cycle.

Shaviv thus concludes the solar-wind modulated CRF hypothesis is "a favorable candidate" for primary instigator of the many climatic phenomena described in this volume.

Even with all the data that have been acquired over the past half-century, it remains difficult to state with much confidence exactly what the world's oceans are doing in terms of the storage and loss of heat. To state precisely *why* they are doing whatever it is they are doing is even more difficult.

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4.2.4.9 South America

As indicated in the introduction of Section 4.2.4, data presented in numerous peer-reviewed studies reveal modern temperatures are not unnatural. For many millennia, Earth's climate has both cooled and warmed independent of its atmospheric CO_2 concentration. Conditions as warm as or warmer than the present have persisted across the Holocene for decades to centuries even though the atmosphere's CO_2 concentration remained at values approximately 30 percent lower than today's.

The following subsections highlight studies addressing this topic in South America. Much of the material focuses on the most recent millennium of Earth's history, detailing the historical fluctuations of Earth's climate that long ago ushered in the Roman Warm Period, which gave way to the Dark Ages Cold Period, which was followed by the Medieval Warm Period and subsequent Little Ice Age. These natural climate oscillations are the product of a millennial-scale climate forcing; the Current Warm Period is simply the latest manifestation. Carbon dioxide had little to do with the warmth (or cold) of these prior epochs, and there is no compelling reason to conclude it is having any measurable impact on climate today.

4.2.4.9.1 Argentina

Cioccale (1999) assembled what was known at the time about the climatic history of the central region of Argentia over the past 1,400 years, highlighting a climatic "improvement" that began 400 years before the start of the last millennium, which ultimately came to be characterized by "a marked increase of environmental suitability, under a relatively homogeneous climate." As a result of this climatic amelioration that marked the transition of the region from the Dark Ages Cold Period to the Medieval Warm Period, Cioccale reports "the population located in the lower valleys ascended to higher areas in the Andes," where they remained until around AD 1320, when the transition to the stressful and extreme climate of the Little Ice Age began.

At the southern tip of the country, in Tierra del Fuego, Mauquoy *et al*. (2004) inferred similar changes in temperature and/or precipitation from plant macrofossils, pollen, fungal spores, testate amebae, and humification associated with peat monoliths collected from the Valle de Andorra. These new chronologies were compared with other chronologies from both the Southern and Northern Hemispheres, and the analysis showed evidence for a period of warming-induced drier conditions in AD 960–1020, which, they write, "seems to correspond to the Medieval Warm Period (MWP, as derived in the Northern Hemisphere)." They also note, "this interval compares well to the date range of AD 950–1045 based on Northern Hemisphere extratropical tree-ring data (Esper *et al*., 2002)." They conclude this correspondence "shows that the MWP was possibly synchronous in both hemispheres, as suggested by Villalba (1994)."

Haberzettl *et al*. (2005) worked with five sediment cores extracted from Laguna Potrok Aike (51°58'S, 70°23'W), one of the few permanently water-filled lakes in the dry-lands of southern Patagonia. They analyzed a host of proxy climate indicators, finding "the sediment record of Laguna Potrok Aike reveals an unprecedented sensitive continuous high resolution lake level, vegetation and climate record for southern Patagonia since AD 400." This history indicates the climate of the region fluctuated rapidly from the beginning of the record up to the start of the Medieval Climatic Anomaly (MCA), which Stine (1998) proposed as having begun at about AD 870. This earlier time interval corresponds with the Dark Ages Cold Period of Europe, and it was followed by the MCA, or what

Europeans call the Medieval Warm Period. The latter was most strongly expressed in the Laguna Potrok Aike data from AD 1240 to 1410, during which period maxima of total inorganic carbon (TIC), total organic carbon (TOC), total nitrogen (TN), carbon/nitrogen ratio (C/N) and δ^{13}Corg indicate, in the words of the ten researchers, "low lake levels and warm and dry climate."

Thereafter, the scientists continue, "the MCA ends during the 15th century" and was "followed by the so called 'Little Ice Age.'" Finally, they write, "in the course of the 20th century, Laguna Potrok Aike reacted like many other Patagonian lakes with a lake level lowering after 1940, culminating in 1990, and followed by a subsequent rise and recession."

As to whether it was warmer during the MCA than during the twentieth century, Haberzettl *et al*. state, "there is evidence for lower lake levels during the MCA than today in every proxy," and "the existence of lower lake levels in former times was demonstrated by seismic studies which revealed hitherto undated fossil lake level terraces ca. 30 m below the present lake level (Zolitschka *et al*, 2004)." In addition, "TOC and TN as proxies reflecting productivity also show higher values during the MCA than today," even though "present TOC and TN values are elevated due to anthropogenic eutrophication." They conclude, "this altogether implies that it might have been warmer during [AD 1240 to 1410] than today."

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4.2.4.9.2 Brazil

Vuille *et al*. (2012) reviewed the history of the South American summer monsoon (SASM) over the past two millennia, using information obtained from high-resolution stable isotopes derived from speleothems, ice cores, and lake sediments acquired from the monsoon belt of the tropical Andes and Southeast Brazil. This work reveals "a very coherent behavior over the past two millennia with significant decadal to multidecadal variability superimposed on large excursions during three key periods: the Medieval Climate Anomaly (MCA), the Little Ice Age (LIA) and the current warm period (CWP)," which they interpret as "times when the SASM's mean state was significantly weakened (MCA and CWP) and strengthened (LIA), respectively."

The nine researchers hypothesize, "these centennial-scale climate anomalies were at least partially driven by temperature changes in the Northern Hemisphere and in particular over the North Atlantic, leading to a latitudinal displacement of the Intertropical Convergence Zone and a change in monsoon intensity (amount of rainfall upstream over the Amazon Basin)." As they note the intensity of the SASM "today appears on par with conditions during the MCA," it can be concluded the peak temperatures of the MCA and the CWP over the North Atlantic Ocean are likely on par as well, suggesting there is nothing unusual about today's current level of warmth over the North Atlantic and today's global level of warmth need not have been caused by the concurrent 40 percent greater atmospheric CO_2 concentration.

Reference

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4.2.4.9.3 Chile

Lamy *et al*. (2001) used the iron content from an ocean sediment core taken from the Chilean continental slope (41°S, 74.45°W) as a proxy for historic rainfall in this region during the Holocene. Results indicate several centennial and millennial-scale phases of rainfall throughout this period, including an era of decreased rainfall "coinciding with the Medieval Warm Period," which was followed by an era of increased rainfall during the Little Ice Age (see Figure 4.2.4.9.3.1). They conclude their data "provide further indications that both the LIA and MWP were global climate events."

Jenny *et al*. (2002) studied geochemical, sedimentological, and diatom-assemblage data derived from sediment cores extracted from one of the largest natural lakes (Laguna Aculeo) in the central part of Chile. From 200 BC, when the record began, until AD 200, conditions there were primarily dry, during the latter stages of the Roman Warm Period. Subsequently, from AD 200–700, with a slight respite in the central hundred years of that period, there was a high frequency of flood events, during the Dark Ages Cold Period. Then came a several-hundred-year period of less flooding that was coeval with the Medieval Warm Period. This more benign period was followed by another period of frequent flooding from 1300–1700 coincident with the Little Ice Age, after which flooding picked up again after 1850.

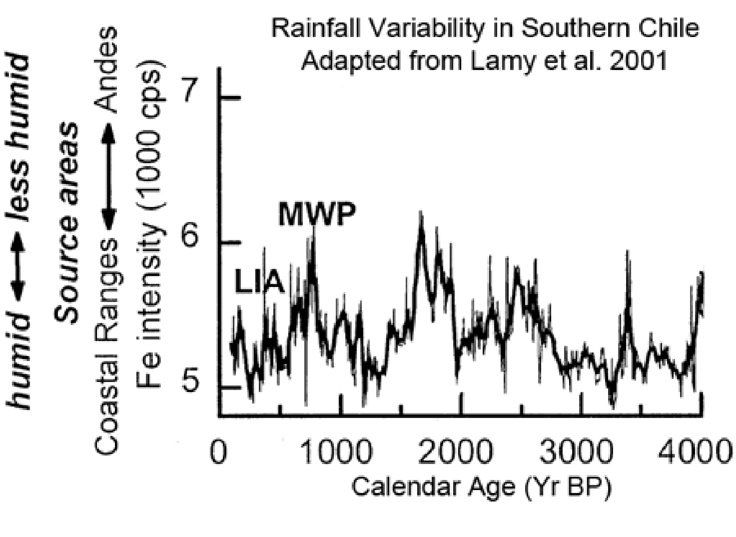

Figure 4.2.4.9.3.1. Reconstructed rainfall record for southern Chile. Adapted from Lamy, F., Hebbeln, D., Röhl, U., and Wefer, G. 2001. Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies. *Earth and Planetary Science Letters* **185**: 369–382.

Nester *et al*. (2007) studied fluvial terraces in the Pampa del Tamarugal (PdT) basin of the Atacama Desert of northern Chile, which contains widespread fossil wood, *in situ* roots, and well-preserved leaf litter deposits indicative of perennial surface flow in now-dry channels where streams once cut canyons in the desert's currently hyper-arid core. In this challenging environment, and based on radiocarbon dating, the five researchers determined the approximate dates of the most important recharge events of these channels of the last 18,000 years, demonstrating "there was enhanced stream discharge into the PdT during the time intervals of 17,750–13,750, 11,750, and 1,100–700 cal yr BP," while noting "groundwater must have been near the surface (<10 m) for *Prosopis* stands to have lived [there] between 1,100–700 cal yr BP." The latter Chilean "Medieval Climatic Anomaly (MCA)," as they describe it, "is of opposite hydrological impact (wet) to that of coastal Peru (dry), where lithic concentrations in a marine core document diminished strength of El Niño events during the MCA (Rein *et al*., 2004)."

This wettest interval of the past 11,000-plus years in the hyper-arid core of the Atacama Desert (~AD 900–1300) coincides nicely with the central portion of the mean timeframe of the MWP as experienced around the globe. This unique set of regional circumstances—wet in the Atacama Desert of Chile and dry along coastal Peru—is a strong indication of the dramatic but varied effects of the global Medieval Warm Period in this particular part of the world.

Rebolledo *et al*. (2008) analyzed changes in marine productivity and contemporaneous terrestrial input in a study of sediment cores retrieved from the Jacaf Channel (44°S, 72°W) of Chilean Northern Patagonia that contained data pertaining to the past 1,800 years, using biogenic opal, siliceous microorganisms, alkenones, and organic (Corg content, molar C/N) and inorganic (Cinorg, Fe, Ti, Ca) elements as proxies for terrestrial input and/or carbonate productivity. They compared their findings with those of other researchers who had conducted similar paleoclimatic studies in various parts of South America and Antarctica.

The seven scientists reported, "the down-core record clearly shows two productivity/climate modes." As they describe it, the first period—prior to 900 cal yr BP and including the Medieval Warm Period (MWP)—is characterized by "decreased marine productivity and a reduced continental signal, pointing to diminished precipitation and runoff." The second period—between 750 cal yr BP and the late 1800s, and including the Little Ice Age (LIA)—is characterized by "elevated productivity and an increased continental signal, suggesting higher precipitation and runoff." In addition, their data clearly show the MWP and LIA were "separated by a relatively abrupt transition of ~150 years." In addition to providing another demonstration of the reality of the MWP and LIA in South America, the Chilean, German, and U.S. scientists conclude the good correspondence between their record and various "other paleoclimate studies carried out in South America and Antarctica demonstrates that the Chilean fjord area of Northern Patagonia is not just sensitive to local climatic variability but also to regional and possibly global variability."

von Gunten *et al*. (2009) write, "quantitative high-resolution global, hemispherical and regional climate reconstructions covering the last millennium are fundamental in placing modern climate warming into a long-term context," in order to "assess the sensitivity of the climate system to natural and anthropogenic forcings, and thus to reduce uncertainty about the magnitude and impact of future global climate change." They note, for the entire Southern Hemisphere, "Mann and Jones (2003) considered only five data sets suitable for their work on surface temperature reconstructions for the past two millennia," and "only two of these data series are from South America," one of which is a tree-ring record "with unknown preservation of the low-frequency component of climate variability" and the other a $\delta^{18}O$ ice core record they describe as "arguably putative at best" in terms of its temperature signal.

von Gunten *et al*. developed a continuous high-resolution (1–3 years sampling interval, five-year filtered reconstruction) austral summer (December to February) temperature reconstruction based on chloro-pigments derived from algae and phototrophic bacteria found in sediment cores retrieved from Central Chile's Laguna Aculeo (33°50'S, 70°54'W) in 2005 that extended back to AD 850, which they describe as "the first quantitative temperature reconstruction for Central Chile for the last millennium." The Swiss, German, and UK scientists report their data provided "quantitative evidence for the presence of a Medieval Climate Anomaly (in this case, warm summers between AD 1150 and 1350; ΔT = +0.27 to +0.37°C with respect to (wrt) twentieth century) and a very cool period synchronous to the 'Little Ice Age' starting with a sharp drop between AD 1350 and AD 1400 (-0.3°C/10 years, decadal trend) followed by constantly cool (ΔT = -0.70 to -0.90°C wrt twentieth century) summers until AD 1750."

The graph of their data, as presented in Figure 4.2.4.9.3.2, indicates the peak warmth of the Medieval Climate Anomaly was about 0.7°C warmer than the last decade or so of the twentieth century, but only about 0.25°C warmer than the peak warmth of the twentieth century, which occurred in the late 1940s in their reconstructed temperatures and their instrumental data, which are essentially identical over most of the 1900s. In addition, they note, the "structure of variability" shown in their data "is consistent in great detail with annually resolved tree-ring-based warm-season temperature and river discharge reconstructions from northern Patagonia for the past 400 years, with qualitative climate reconstructions from Andean glacier fluctuations, and with hydrological changes in Patagonian lake sediment records."

The work of the five researchers thus clearly demonstrates the existence of both the Medieval Warm Period (MWP) and Little Ice Age in the Southern Hemisphere, as well as the fact that the MWP was warmer (and for much longer) than the Current Warm Period has been to date. This suggests there is nothing unnatural about the planet's current level of warmth, or the rate at which it was reached, and thus removes any need to invoke current higher concentrations of atmospheric CO_2 as the cause of these nondescript features of our current climate.

Sepulveda *et al*. (2009) write, "deciphering climate variability in the Southern Hemisphere and particularly from southern South America—the only continental land mass lying between 38°S and the Antarctic Circle—is crucial for documenting the inter-hemispheric synchronicity of recent abrupt

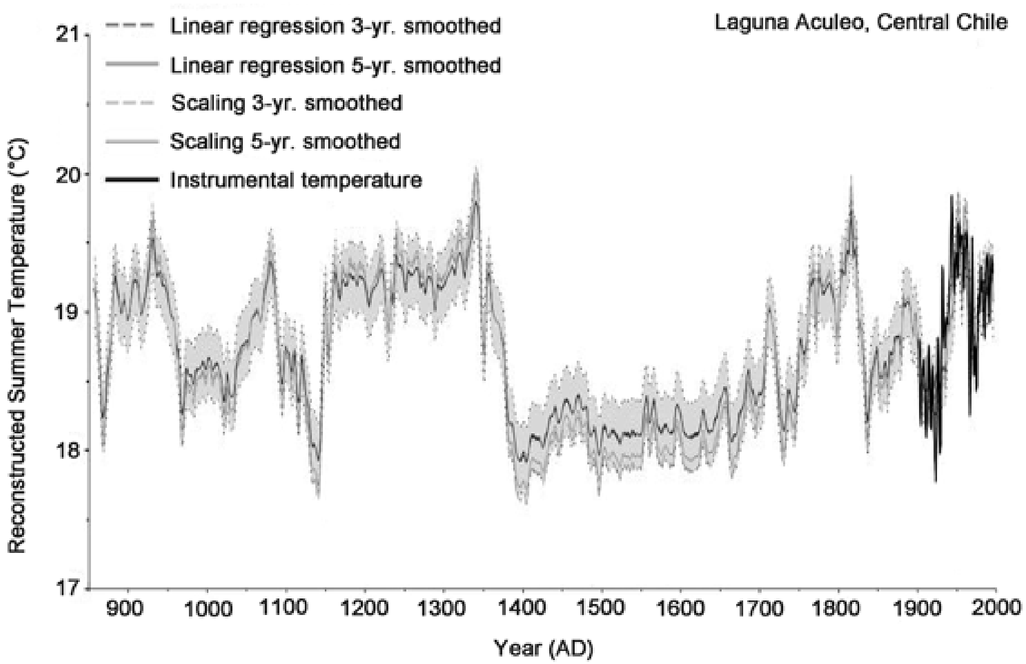

Figure 4.2.4.9.3.2. Proxy temperature reconstruction since AD 850 based on sedimentary pigments from a lake in central Chile. Adapted from von Gunten, L., Grosjean, M., Rein, B., Urrutia, R., and Appleby, P. 2009. A quantitative high-resolution summer temperature reconstruction based on sedimentary pigments from Laguna Aculeo, central Chile, back to AD 850. *The Holocene* **19**: 873–881.

climate changes and thereby determining their ultimate cause(s)," as well as for "predicting future abrupt climate changes." The eight researchers conducted "a high-resolution multi-proxy study including the elemental and isotopic composition of bulk organic matter, land plant-derived biomarkers, and alkenone-based sea-surface temperature (SST) [derived] from a marine sedimentary record obtained from the Jacaf Fjord in northern Chilean Patagonia [44°20.00'S, 72°58.15'W]" to provide "a detailed reconstruction of continental runoff, precipitation and summer SST spanning the last 1750 years."

The Chilean, German, and U.S. scientists report they "observed two different regimes of climate variability in [the] record: a relatively dry/warm period before 900 cal yr BP (higher runoff and average SST 1°C warmer than present day) and a wet/cold period after 750 cal yr BP (higher runoff and average SST 1°C colder than present day)," which they associate with the Medieval Warm Period and Little Ice Age, respectively. They conclude, "the reasonably good correlation between our results (particularly SST) and other continental and marine archives from central-south Chile, Peru, and Antarctica ... confirms the occurrence of globally important climatic anomalies such as the Medieval Warm Period and the Little Ice Age."

Solari *et al*. (2010) obtained a $\delta^{18}O$ record stretching back in time about 1,200 years from the shore of Lago Sarmiento (51°03'00"S, 72°45'01"W) in southern Chile, where massive dead carbonate microbialites are exposed, to which they applied a "well-established, temperature-dependent oxygen isotope equilibrium fractionation equation between calcite and water" that yielded values of surface water temperature at a number of dates, the two oldest of which (AD 800 and 1100) bracketed the MWP at that location. The warmest of these values was 9.5°C, which was 1.26°C greater than the mean surface water temperature of 8.24°C they calculated from actual temperature measurements made every 20 minutes from April 1, 2003 to March 15, 2004. A $\delta^{18}O$-based surface water temperature of 8.9°C is indicated fairly close to the present. Calculated conservatively, the peak temperature of the MWP was likely 0.6°C greater than the peak of the CWP.

Fletcher and Moreno (2012) "sampled and analyzed sediment cores from Laguna San Pedro (38°26'S, 71°19'W)," which they describe as "a small closed-basin lake located within the present-day distribution of *Araucaria-Nothofagus* forest in the Temperate-Mediterranean Transition zone in the Andes of Chile," where they reconstructed the vegetation, climate, and fire regime histories of the past 1,500 years. They found evidence of "persistent cool/La Nina ENSO states" during the periods 1300–1000 and 725–121 cal yr BP, which they identify as the "Dark Ages Cold Period and Little Ice Age, respectively." In addition, they report finding evidence of "low relative growing season moisture and warmer temperature that correspond well with evidence for persistent warm/El Nino ENSO states (1500–1300 and 1000–725 cal yr BP)," which they respectively associate with the Roman Warm Period and Medieval Climate Anomaly. Regarding the transition from the Little Ice Age to the Current Warm Period, which occurred from 121 cal yr BP (AD 1829) to the present, they found evidence for "a dramatic landscape alteration associated with the arrival of exotic taxa and an increase in burning," which they attribute to European colonization of the area. Fletcher and Moreno also state, "the palaeo-environmental history inferred from Laguna San Pedro provides important palaeo-climatic information for this part of southern South America that is poorly represented in the palaeo-climate literature."

Elbert *et al*. (2013) analyzed sediment cores from Laguna Escondida (45°31'S, 71°49'W) in Northern Chile for biogenic silica (bSi) concentrations, which they compared with modern meteorological data from the CRU TS 3.0 reanalysis data set (Mitchell and Jones, 2005; 0.5°x0.5° grid cell 45°S/72°W), while using radiometric dating (^{210}Pb, ^{137}Cs, ^{14}C-MS) to place the entire set of results in a temporally correct perspective. The result is depicted in Figure 4.2.4.9.3.3, showing the peak warmth of the Medieval Warm Period (~AD 920–1180) was about 2.9°C greater than the most recent sediment-derived Current Warm Period temperatures.

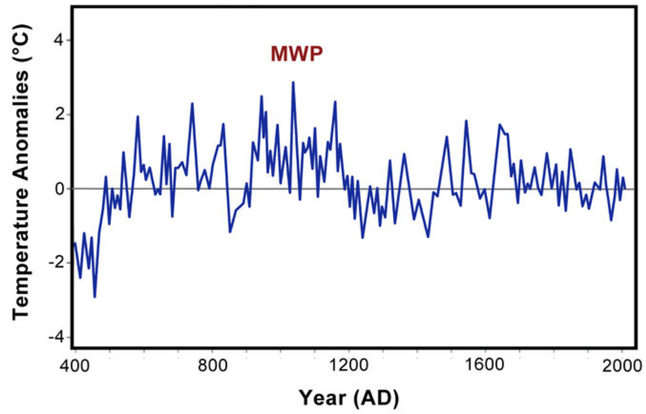

Figure 4.2.4.9.3.3. Proxy temperature reconstruction since AD 400 from a lake in northern Chile. Adapted from Elbert, J., Wartenburger, R., von Gunten, L., Urrutia, R., Fischer, D, Fujak, M., Hamann, Y., Greber, N.D., and Grosjean, M. 2013. Late Holocene air temperature variability reconstructed from the sediments of Laguna Escondida, Patagonia, Chile (45°30'S). *Palaeogeography, Palaeoclimatology, Palaeoecology* **369**: 482–492.

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4.2.4.9.4 Peru

Chepstow-Lusty *et al*. (1998) derived a 4,000-year climate history from a study of pollen in sediment cores obtained from a recently in-filled lake in the Patacancha Valley near Marcacocha. Their data indicate a several-century decline in pollen content after AD 100, as the Roman Warm Period gave way to the Dark Ages Cold Period. A "more optimum climate," as they describe it, with warmer temperatures and drier conditions, prevailed for several centuries after about AD 900, the Medieval Warm Period, followed by the Little Ice Age. These climatic periods are in nearly perfect temporal agreement with the climate history derived by McDermott *et al*. (2001) from a study of a stalagmite recovered from a cave nearly half the world away in Ireland.

Subsequent work in this area was conducted by Chepstow-Lusty and Winfield (2000). They identify "the warm global climatic interval frequently referred to as the Medieval Warm Epoch" centered on approximately 1,000 years ago. This extremely arid interval in this part of South America, in their opinion, may have played a significant role in the collapse of the Tiwanaku civilization further south, where a contemporaneous prolonged drought occurred in and around the area of Lake Titicaca (Binford *et al*., 1997; Abbott *et al*., 1997).

Near the start of this extended dry period, which established itself gradually between about AD 700 and 1000, Chepstow-Lusty and Winfield report, "temperatures were beginning to increase after a sustained cold period that had precluded agricultural activity at these altitudes." This earlier colder and wetter interval was coeval with the Dark Ages Cold Period of the North Atlantic region, which in the Peruvian Andes prevailed for much of the millennium preceding AD 1000, as revealed by a series of climatic records developed from sediment cores extracted from other lakes in the Central Peruvian Andes (Hansen *et al*., 1994) and by proxy evidence of concomitant Peruvian glacial expansion (Wright, 1984; Seltzer and Hastorf, 1990).

Preceding the Dark Ages Cold Period in both parts of the world was what in the North Atlantic region is called the Roman Warm Period. This well-defined climatic epoch is also strikingly evident in the pollen records of Chepstow-Lusty *et al*. (2003), straddling the BC/AD calendar break with one to two hundred years of relative warmth and significant aridity on both sides of it.

Data compiled by Chepstow-Lusty *et al*. (2003) reveal the occurrence of the Little Ice Age, which in the Central Peruvian Andes was characterized by relative coolness and wetness. These characteristics of that climatic interval are also evident in ice cores retrieved from the Quelccaya ice cap in southern Peru, the summit of which extends 5,670 meters above mean sea level (Thompson *et al*., 1986, 1988). Both the Quelccaya ice core data and the Marcacocha pollen data indicate the transition to the drier Current Warm Period that occurred over the past 100-plus years.

Rein *et al*. (2004) derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima. They found a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the Medieval period. They report, "lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250" (see Figure 4.2.4.9.4.1). They write, "all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly." In addition, "this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain," citing 11 references in support of this statement.

Consequently, because heavy winter rainfalls

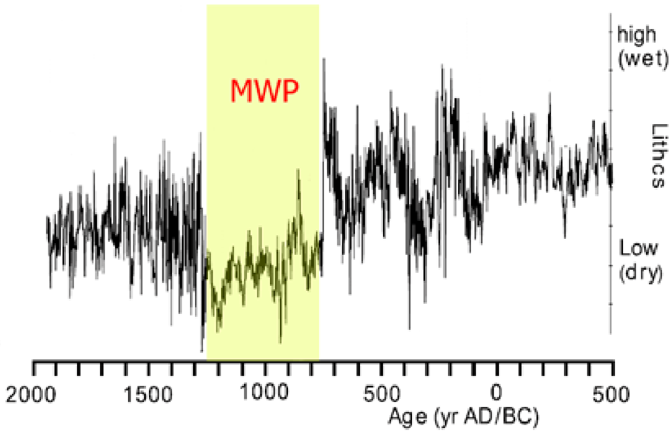

Figure 4.2.4.9.4.1. Marine record of El Niño flood sediments off Peru, as derived from lithic concentrations. Adapted from Rein B., Lückge, A., and Sirocko, F. 2004. A major Holocene ENSO anomaly during the Medieval period. *Geophysical Research Letters* **31**: 10.1029/2004GL020161.

along and off coastal Peru occur only during times of maximum El Niño strength, and because El Niños are typically more prevalent and stronger during cooler as opposed to warmer periods, the lack of strong El Niños from A.D. 800 to 1250 suggests this period was truly a Medieval Warm Period. The significance of this observation was not lost on Rein *et al*. In the introduction to their paper, for example, they observe, "discrepancies exist between the Mann curve and alternative time series for the Medieval period." Most notably, they write, "the global Mann curve has no temperature optimum, whereas the Esper *et al*. (2002) reconstruction shows northern hemisphere temperatures almost as high as those of the 20th century" during the Medieval Warm Period. Rein *et al.* conclude, "the occurrence of a Medieval climatic anomaly (A.D. 800–1250) with persistently weak El Niños may therefore assist the interpretation of some of the regional discrepancies in thermal reconstructions of Medieval times," a polite way of suggesting the Mann *et al*. (1998, 1999) hockey stick temperature history is deficient in failing to identify a true Medieval Warm Period.

Rein *et al*. (2005) derived sea surface temperatures from alkenones extracted from a high-resolution marine sediment core retrieved off the coast of Peru (12.05°S, 77.66°W), spanning the past 20,000 years and ending in the 1960s. Their Figure 11, reproduced here as Figure 4.2.4.9.4.2, shows the warmest temperatures of this 20,000 year period (~23.2°C) occurred during the late Medieval time (AD 800–1250). Taking this value, 23.2°C, and comparing it with the modern monthly long-term means in sea surface temperature, which the authors characterize as between 15°C and 22°C, the peak warmth of the Medieval Warm Period for this region was about 1.2°C above that of the Current Warm Period.

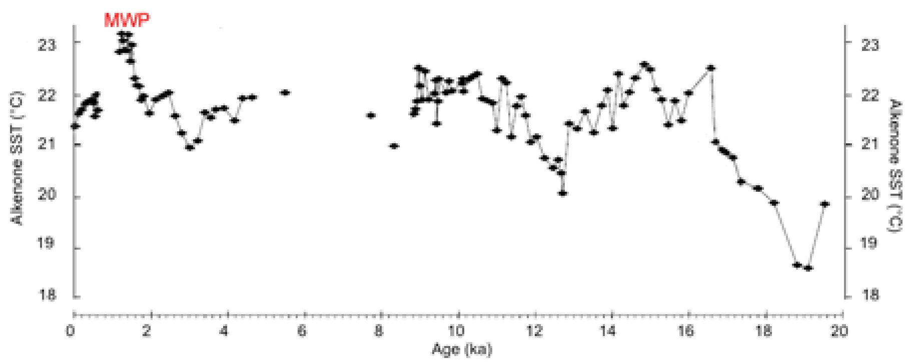

Figure 4.2.4.9.4.2. Coastal Peru proxy sea surface temperatures. Adapted from Rein B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., and Dullo, W.-C. 2005. El Niño variability off Peru during the last 20,000 years. *Paleoceanography* **20**: 10.1029/ 2004PA001099.

Sterken *et al*. (2006) conducted a quantitative diatom analysis on a sediment core obtained from the small infilled lake basin of Marcacocha, in the Cuzco region of the south central Andes mountains of Peru (13.22°S, 72.2°W) to reconstruct environmental changes during the past 1,200 years. The data indicated a major climate transition around AD 1070, representing "the most prominent change in the diatom record with a marked shift towards higher temperatures."

Unkel *et al*. (2007) employed "geomorphological field-work" and "chronometric analyses"—consisting of conventional ^{14}C-dating of charcoal, wood and root samples and optical-stimulated luminescence dating of feldspar and quartz—while investigating "alluvial archives and debris flow deposits" in the hyper-arid zone of the northern Atacama Desert of Peru between Pisco/Ica and Nazca/San Juan (~14.3°S, 75.3°W). This work, together with others', indicates the existence of a period of "fluvial silence" for "the time of the 9th-13th centuries," due to "increased aridification," which they associated with the Medieval Warm Period (~AD 800–1250).

Bird *et al*. (2011) developed a 2,300-year history of the South American Summer Monsoon (SASM) from an annually resolved authigenic calcite record of precipitation $\delta^{18}O$ obtained from a varved lake in the Central Peruvian Andes—Laguna Pumacocha (10.70°S, 76.06°W, 4300 m asl). Their history shows, they write, "$\delta^{18}O$ peaked during the Medieval Climate Anomaly (MCA) from AD 900 to 1100, providing evidence the SASM weakened considerably during this period." Thereafter, they found, "minimum $\delta^{18}O$ values occurred during the Little Ice Age (LIA) between AD 1400 and 1820, reflecting a prolonged intensi-fication of the SASM," after which "$\delta^{18}O$ increased rapid-ly, particularly during the Current Warm Period (CWP; AD 1900 to present), indi-cating a return to reduced SASM precipitation."

The six scientists also note the Pumacocha record tracks the 900-year-long Cascayunga Cave $\delta^{18}O$ record (6.09°S, 77.23°W, 930 m asl), which they say "is interpreted as a record of South American rainfall (Reuter *et al*., 2009)." They report it shares many features with the annually resolved Quelccaya Ice Cap $\delta^{18}O$ record (13.93°S, 70.83°W, 5670 m asl) derived by Thompson *et al*. (1986). They state, "the close agreement in the timing, direction, and magnitude of mean state changes in $\delta^{18}O$ during the MCA, LIA, and CWP from lake sediment, speleothem, and ice core records supports the idea that a common large-scale mechanism influenced $\delta^{18}O$ reaching these central Andean sites spanning 11° latitude and 4,740 meters of elevation." They conclude, "the most likely cause of these documented shifts in $\delta^{18}O_{precip}$ is a change in SASM intensity, as all three sites receive the majority of their annual precipitation during the monsoon season."

Bird *et al*. also describe the "remarkable correspondence" that exists between the Pumacocha $\delta^{18}O$ record of SASM rainfall and the 2,000-year Northern Hemispheric temperature reconstruction of Moberg *et al*. (2005), plus the similar relationship both records share with the somewhat-shorter North Atlantic temperature reconstruction of Mann *et al*. (2009). Specifically, they indicate "the two greatest reductions in SASM intensity in the Pumacocha $\delta^{18}O$ record were coincident with Northern Hemisphere temperature maxima during the MCA and CWP," and "the SASM was stronger than at any other point in the last 2,300 years when Northern Hemisphere temperatures were at a 2,000-year low during the LIA." As noted above, their data show the same relationships exist between the Pumacocha $\delta^{18}O$ history and the North Atlantic temperature history.

Especially interesting about these observations is that Bird *et al*.'s graphical representations of the Northern Hemisphere and North Atlantic temperature histories of Moberg *et al*. and Mann *et al*. both show the peak warmth of the MCA to be at least as great as, and possibly even a little greater than, the peak warmth of the CWP, plus the fact that the $\delta^{18}O$ data of Bird *et al*. suggest much the same thing, based upon what they call the "remarkable correspondence" among the three datasets, which can be seen in Figure 4.2.4.9.4.3.

As illustrated in this figure, the correspondence among the four datasets is nothing short of astound-ing. The equivalent or slightly greater warmth of the MCA (known also as the Medieval Warm Period or MWP) compared to the CWP would appear to be well-established for the North Atlantic Ocean, the Northern Hemisphere, and a good portion of South America. In support of this conclusion, Bird *et al*. note the diminished SASM precipitation (higher $\delta^{18}O$ data) during the MWP and CWP also tracks the north-ward migration of the Intertropical Convergence Zone over the Atlantic, since "the Pumacocha record shows that the SASM was considerably reduced during the MCA when peak %Ti in the Cariaco Basin record indicates that the Intertropical Convergence Zone was persistently northward," as demonstrated by Haug *et al*. (2001).

A growing body of evidence suggests the Medieval Warm Period of a thousand or so years ago was as warm as or warmer than the Current Warm Period to date. And with the air's CO_2 concentration having risen by some 40 percent since the days of the MWP, without any net increase in temperature, it is unlikely Earth's current warmth is being provided by that increase in the atmosphere's CO_2 content.

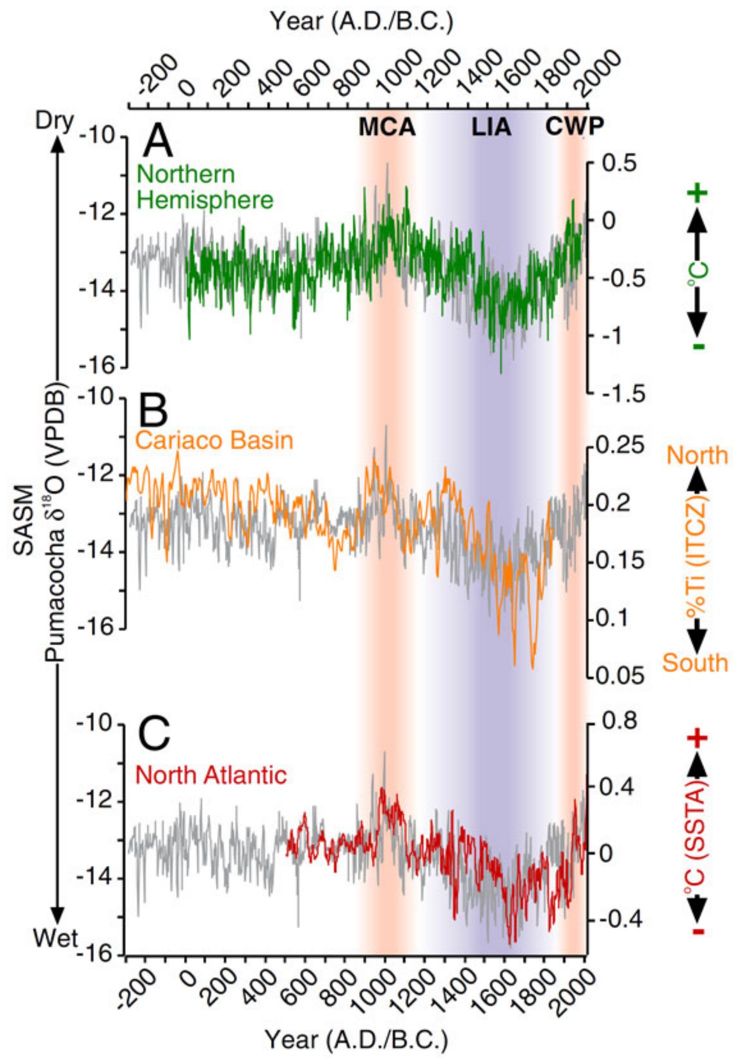

Figure 4.2.4.9.4.3. (A) The reconstructed Northern Hemispheric temperature history of Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlen, W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* **433**: 613–617; (B) the reconstructed North Atlantic temperature history of Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* **326**: 1256–1260; and (C) the Cariaco Basin %Ti data of Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., and Rohl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. *Science* **293**: 1304–1308, which represent the degree of northward migration of the Intertropical Convergence Zone, each plotted together with the δ^{18}O data (gray lines) of Bird *et al*. (2011). Figure adapted from Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D., and Rosenmeier, M.F. 2011. A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences USA* **108**: 8583–8588.

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4.2.4.9.5 Venezuela

Haug *et al*. (2001) found a temperature/precipitation relationship for Venezuela different from that of the rest of the continent. In examining the titanium and iron concentrations of an ocean sediment core taken from the Cariaco Basin on the country's northern shelf, they determined the concentrations of these elements were lower during the Younger Dryas cold period between 12.6 and 11.5 thousand years ago, corresponding to a weakened hydrologic cycle with less precipitation and runoff. During the warmth of the Holocene Optimum of 10.5 to 5.4 thousand years ago, they found, titanium and iron concentrations remained at or near their highest values, suggesting wet conditions and an enhanced hydrologic cycle. Closer to the present, higher precipitation also was noted during the Medieval Warm Period from 1.05 to 0.7 thousand years ago, followed by drier conditions associated with the Little Ice Age between 550 and 200 years ago.

Haug *et al*. (2003) developed a hydrologic history of pertinent portions of the record, which yielded "roughly bi-monthly resolution and clear resolution of the annual signal." According to this record, "before about 150 A.D.," which the climate history of McDermott *et al*. (2001) shows as corresponding to the latter portion of the Roman Warm Period (RWP), Mayan civilization flourished. During the transition to the Dark Ages Cold Period (DACP), which was accompanied by a slow but long decline in precipitation, "the first documented historical crisis hit the lowlands, which led to the 'Pre-Classic abandonment' (Webster, 2002) of major cities," Haug *et al*. report.

This crisis occurred during the first intense multi-year drought of the RWP-to-DACP transition, which was centered on about the year 250 AD Although the drought was devastating to the Maya, when it was over, "populations recovered, cities were reoccupied,

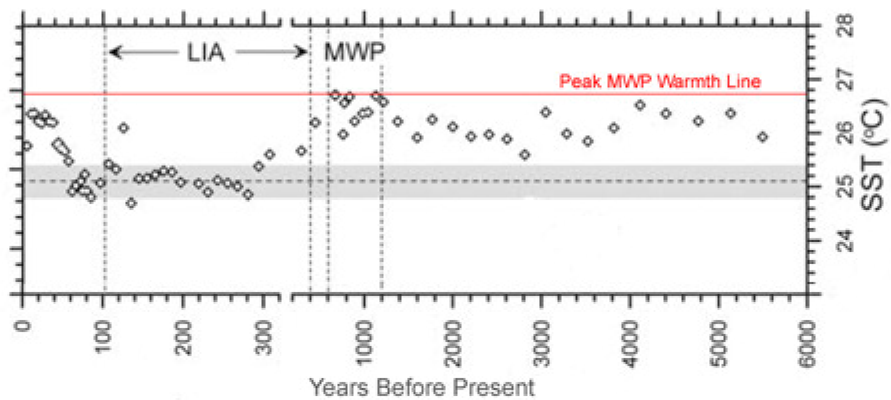

Figure 4.2.4.9.5.1. Alkenone-based SST reconstruction for the Cariaco Basin, Venezuela. Adapted from Goni, M.A., Woodworth, M.P., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Muller-Karger, F., Astor, Y., and Varela, R. 2004. Generation, transport, and preservation of the alkenone-based $U37^{K'}$ sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela). *Global Biogeochemical Cycles* **18**: 10.1029/2003GB002132.

and Maya culture blossomed in the following centuries during the so-called Classic period," Haug *et al*. report. Between about 750 and 950 AD, during what Haug *et al*. determined was the driest interval of the entire Dark Ages Cold Period, "the Maya experienced a demographic disaster as profound as any other in human history" in response to a number of intense multi-year droughts. During this Terminal Classic Collapse, as it is called, "many of the densely populated urban centers were abandoned permanently, and Classic Maya civilization came to an end."

Haug *et al*. conclude the latter droughts "were the most severe to affect this region in the first millennium A.D." Although some of these spectacular droughts were "brief," lasting "only" between three and nine years, Haug *et al*. report "they occurred during an extended period of reduced overall precipitation that may have already pushed the Maya system to the verge of collapse.

Although the Mayan civilization thus faded away, Haug *et al*.'s data soon thereafter depict the development of the Medieval Warm Period, when the Vikings established their historic settlement on Greenland. Then came the Little Ice Age, which just as quickly led to the Vikings' demise in that part of the world. This distinctive cold interval of the planet's millennial-scale climatic oscillation must have also led to hard times for the people of Mesoamerica and northern tropical South America, for the data of Haug *et al*. indicate the Little Ice Age produced by far the lowest precipitation regime (of several hundred years duration) of the last two millennia in that part of the world.

Goni *et al*. (2004) reconstructed a history of sea surface temperatures covering the past 6,000 years for the Cariaco Basin (20°30'N, 64°40'W) on the continental shelf off the central coast of Venezuela, based on the degree of un-saturation of certain long-chain alkenones synthesized by haptophyte algae contained in a sediment core retrieved from the eastern sub-basin.

Figure 4.2.4.9.5.1 shows the highest alkenone-derived sea surface temperatures "were measured during the Medieval Warm Period (MWP)," which Goni *et al*. identify as occurring between AD 800 and 1400. It is also evident peak MWP temperatures were approximately 0.35°C warmer than peak Current Warm Period (CWP) temperatures and fully 0.95°C warmer than the mean temperature of the last decade of the twentieth century.

Rein (2004) obtained high-resolution $\delta^{18}O$ records generated from seasonally representative planktic foraminifera from two ocean sediment cores extracted from the Cariaco Basin off the coast of Venezuela (~10.65°N, 64.66°W) to produce a temperature/salinity reconstruction in this region of the Caribbean/tropical North Atlantic over the last 2,000 years. A general trend toward cooler and perhaps more saline waters over the length of the record was observed. The authors describe discussion of the Medieval Warm Period and Little Ice Age as "complicated," but they acknowledge their record reveals "an interval of warmer [sea surface temperatures] prior to ~ A.D. 1600–1900" where the $\delta^{18}O$ data "correctly sequence the relative temperature change between the so-called MWP and LIA."

According to the authors' graph of *G. bulloides* $\delta^{18}O$ (25-year mean, reproduced here as Figure 4.2.4.9.5.2), along with their stated relationship that a $\delta^{18}O$ change of 1.0‰ is equivalent to a 4.2°C change in temperature, the difference in peak warmth between the MWP and CWP can be calculated as 1.05°C, with the MWP being the warmer of the two

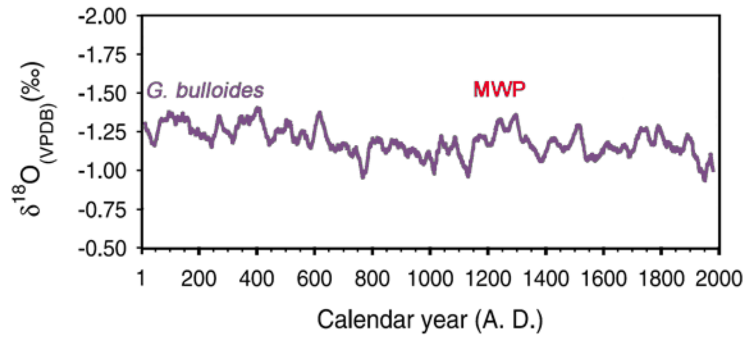

Figure 4.2.4.9.5.2. A high-resolution $\delta^{18}O$ temperature/salinity reconstruction from two ocean sediment cores extracted from the Cariaco Basin off the coast of Venezuela. Adapted from Black, D.E., Thunell, R.C., Kaplan, A., Peterson, L.C., and Tappa, E. J. 2004. A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability. *Paleoceanography* **19**, PA2022, doi:10.1029/ 2003PA000982.

periods.

Polissar *et al*. (2006) derived continuous decadal-scale records of two climate-relevant parameters related to precipitation/ evaporation balance and, hence, glacier activity, from sediment cores extracted from Laguna Blanca (8°20'N, 71°47'W) and Laguna Mucubaji (8°47'N, 70°50'W). Data they obtained from the nearby Piedras Blancas peat bog yielded a third parameter—"pollen histories that chronicle vegetation change in response to climate." All three parameters suggest the MWP was warmer than the CWP.

In the case of Laguna Blanca magnetic suscepti-bility, the MWP's greater warmth extended from before the start of the record (sometime prior to AD 500) to approximately AD 1300. In the case of the abundance of sedge pollen from the Piedras Blancas peat bog, it extended from about AD 550 to 1020, and in the case of altitudinal shifts in ecological zones derived from the Piedras Blancas data, it extended from sometime before the start of the record to about AD 1000. All three datasets thus suggest the MWP, during the period AD 550–1000, was warmer than the CWP.

The Polissar *et al*. study also clearly implicated solar variability as the cause of the climatic variations they observed. The six scientists note, for example, "four glacial advances occurred between AD 1250 and 1810, coincident with solar-activity minima," and they note the data they presented "suggest that solar activity has exerted a strong influence on century-scale tropical climate variability during the late Holocene, modulating both precipitation and tempera-ture," in addition to demonstrating the "considerable sensitivity of tropical climate to small changes in radiative forcing from solar irradiance variability."

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Goni, M.A., Woodworth, M.P., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Muller-Karger, F., Astor, Y., and Varela, R. 2004. Generation, transport, and preservation of the alkenone-based $U37^{K'}$ sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela). *Global Biogeochemical Cycles* **18**: 10.1029/2003GB002132.

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<u>4.2.4.9.6 Other/Multiple Regions</u>

Kellerhals *et al*. (2010) write, "to place recent global warming into a longer-term perspective and to understand the mechanisms and causes of climate change, proxy-derived temperature estimates are needed for time periods prior to instrumental records and regions outside instrumental coverage." They also note "for tropical regions and the Southern

Hemisphere ... proxy information is very fragmentary."

Kellerhals *et al*. developed "a reconstruction of tropical South American temperature anomalies over the last ~1600 years ... based on a highly resolved and carefully dated ammonium record from an ice core that was drilled in 1999 on Nevado Illimani [16°37'S, 67°46'W] in the eastern Bolivian Andes." The researchers note "studies from other remote ice core sites have found significant correlations between $NH4^+$ concentration and temperature for Siberia and the Indian subcontinent for preindustrial time periods," citing the work of Kang *et al*. (2002) and Eichler *et al*. (2009). In calibrating and validating the $NH4^+$-to-°C transfer function, they say they used "the Amazon Basin subset of the gridded HadCRUT3 temperature data set," described by Brohan *et al*. (2006).

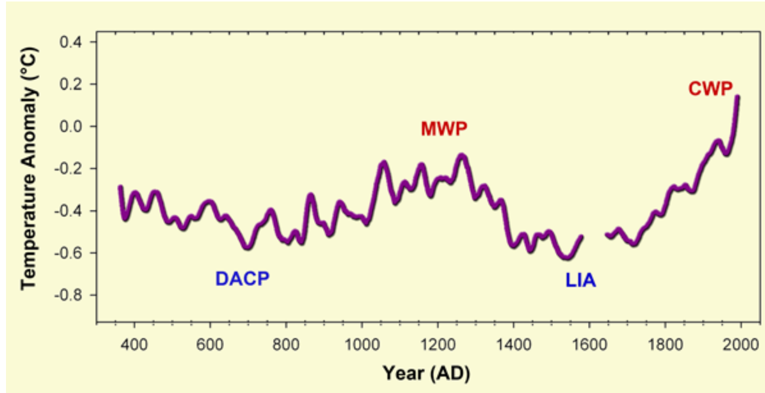

Figure 4.2.4.9.6.1. Reconstructed tropical South American temperature anomalies normalized to the AD 1961–1990 average and smoothed with a 39-year Gaussian filter. Adapted from Kellerhals, T., Brutsch, S., Sigl, M., Knusel, S., Gaggeler, H.W., and Schwikowski, M. 2010. Ammonium concentration in ice cores: a new proxy for regional temperature reconstruction? *Journal of Geophysical Research* **115**: 10.1029/2009JD012603.

The results of this analysis are depicted in Figure 4.2.4.9.6.1. The scientists report, "the most striking features in the reconstruction are [1] the warm temperatures from ~1050 to ~1300 AD [the Medieval Warm Period] compared to the preceding and following centuries, [2] the persistent cooler temperatures from ~1400 to ~1800 AD [the Little Ice Age], and [3] the subsequent rise to warmer temperatures [the Current Warm Period] which eventually seem to exceed, in the last decades of the 20th century, the range of past variation." In regard to this last observation—as best as can be determined from their graph of the data—the peak warmth of the Current Warm Period was ~0.27°C greater than the peak warmth of the Medieval Warm Period.

Kellerhals *et al*. note the terms Little Ice Age (LIA) and Medieval Warm Period (MWP) can be validly employed to describe the "extensive advances of alpine glaciers in Europe from the 16th to the 19th century and the comparatively warm conditions in Europe from the 10th to the 13th century." However, they add, the implication that these terms represent "globally synchronous cold and warm periods" has been dismissed by the IPCC and others. Kellerhals *et al*. conclude the "relatively warm temperatures during the first centuries of the past millennium and subsequent cold conditions from the 15th to the 18th century suggest that the MWP and the LIA are not confined to high northern latitudes," and they "also have a tropical signature." These observations add to the growing body of evidence demonstrating the global extent of the millennial-scale oscillation of climate that produced both the MWP and the LIA, and which has likely been responsible for the bulk of the warming that led to the establishment of the Current Warm Period.

Neukom *et al*. (2011) reconstructed a mean austral summer (December–February) temperature history for the period AD 900–1995 for the terrestrial area of the planet located between 20°S and 55°S and between 30°W and 80°W—a region they call Southern South America (SSA)—using 22 of the best climate proxies they could find that stretched far enough back in time. Their results, they note, "represent the first seasonal sub-continental-scale climate field reconstructions of the Southern Hemisphere going so far back in time." Such an analysis, the authors state, was necessary "to put the recent warming into a larger temporal and spatial context."

According to the international research team—composed of scientists from Argentina, Chile, Germany, Switzerland, The Netherlands, the United Kingdom, and the United States—their summer temperature reconstruction indicates "a warm period extended in SSA from 900 (or even earlier) to the mid-fourteenth century," which they describe as having been "towards the end of the Medieval Climate Anomaly as concluded from Northern Hemisphere temperature reconstructions." As depicted in Figure 4.2.4.9.6.2, their calculations show

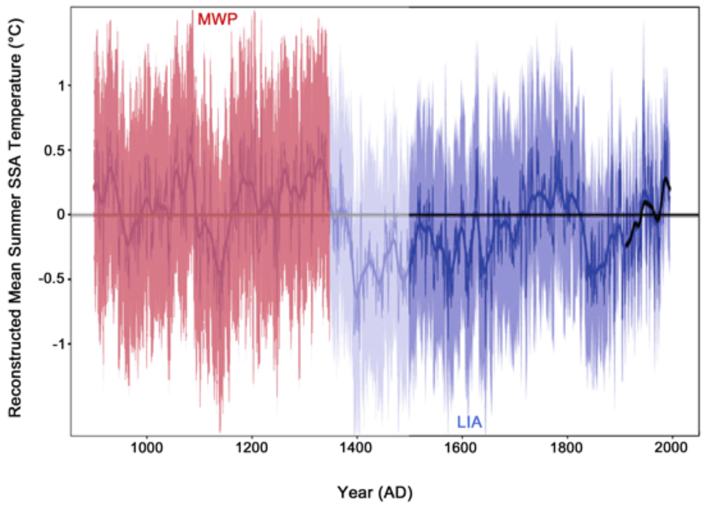

Figure 4.2.4.9.6.2. Reconstructed mean summer SSA temperatures. Adapted from Neukom, R., Luterbacher, J., Villalba, R., Kuttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.-C., Black, D.E., Christie, D.A., D'Arrigo, R., Lara, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urritia, R., and von Gunten, L. 2011. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* **37**: 35–51.

the warmest decade of this Medieval Warm Period was AD 1079–1088, which, as best as can be determined from their graph, is about 0.17°C warmer than the peak warmth of the Current Warm Period.

Bracco *et al*. (2011) studied the emergence and development of prehistoric mound building in southeast Uruguay, employing paleoclimatic data to obtain a picture of how the climate of the region changed in the past 7,000 years. Focusing on the coastal lagoons within the Merin Lagoon basin, located between 31–34°S and 52–54°W in the easternmost part of the South American plains, Bracco *et al*. say paleolimnological investigations were initiated there in AD 2000 by a multidisciplinary group of researchers who studied past climate conditions via "multiproxy analyses (i.e., diatoms, opal phytoliths, pollen, molluscs, sediments, geo-chemistry, thin sections), together with radiocarbon dating." Working predominantly with phytoliths found in various sediment cores, they derived 7,000-year histories of both temperature and a humidity index.

The South American scientists found a period (AD 750–1350) "characterized by warmer and wetter conditions than those of the present," which matches well with the timeframe of the Medieval Warm Period. Within this period, they write, "there are two peaks of extreme humid and warm events," the second of which "fits chronologically into the 'Warm Period' (Broecker, 2001; Roberts, 2009), whose occurrence has been already pointed out by Iriondo and Garcia (1993) and Prevosti *et al*. (2004) in this region."

These findings help confirm the global nature of the Medieval Warm Period. Bracco *et al*. also note their results "are consistent with other paleoclimatic reconstructions (Bracco *et al*., 2005; Garcia-Rodriguez *et al*., 2009) and the synthesis presented by Mancini *et al*. (2005), and they are partially consistent with other regional studies (Iriondo and Garcia, 1993; Prieto, 1996, 2000; Iriondo, 1999; Panario and Gutierrez, 1999; Tonni *et al*., 1999; Zarate *et al*., 2000; Prieto *et al*., 2004; Quattrocchio *et al*., 2008; Piovano *et al*., 2009, in Argentina; Behling, 1995, 2002, 2007; Melo *et al*., 2003; Moro *et al*., 2004, in Brazil." This growing body of empirical findings is evidence of the millennial-scale cycling of our planet's climate, which after the passing of the Little Ice Age that followed the Medieval Warm Period is likely what has most recently ushered us into the Current Warm Period.

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4.3 Predicted vs. Observed Global Warming Effects on ENSO

Computer model simulations have given rise to three claims regarding the influence of global warming on ENSO events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions (see, for example, Timmermann *et al*., 1999; Collins 2000a,b; Cubasch *et al*., 2001). However, as outlined in the following two subsections, this is generally not what observational data show. The data for nearly all historical records show frequent and strong El Niño activity increases during periods of colder temperatures (e.g., the Little Ice Age) and decreases during warm ones (e.g., Medieval Warm Period, Current Warm Period).

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4.3.1 Frequency and Intensity

Mendelssohn *et al*. (2005) performed a statistical analysis known as state-space decomposition on three El Niño-related indices (Southern Oscillation Index, its component sea level pressure series, and the NINO3 index) for the twentieth century. The stochastic cycles produced by the state-space models were all relatively stationary, which, in the words of the investigative scientists, does "not support the idea that El Niños have become more frequent." As to the magnitude of ENSO events, they say there were some "outlier events" in the later portion of the record, which may suggest ENSO magnitudes have increased in recent years, but they conclude "it is premature to tell."

Lee and McPhaden (2010) used satellite observations of sea surface temperature (SST) in the past three decades "to examine SST in the CP region, distinguishing between the increases in El Niño intensity and changes in background SST." The two U.S. researchers discovered the SSTs in the CP region during El Niño years are "getting significantly higher while those during La Niña and neutral years are not." Therefore, they reason, "the increasing intensity of El Niño events in the CP region is not simply the result of the well-documented background warming trend in the western-Pacific warm pool," but instead "it is the increasing amplitude of El Niño events that causes a net warming trend of SST in the CP region."

Lee and McPhaden conclude their results "suggest that, at least for the past three decades, the warming of the warm pool in the CP region is primarily because of more intense El Niño events in that region." In addition, they report, "in contrast to the CP region, the intensity of El Niño events in the EP region does not have a warming trend, and even has a cooling trend (though not significant at the 90% level of confidence) over the three-decade period." They write, "further investigation is therefore needed to understand these issues better, given the uncertainty surrounding causal mechanisms and the implications the observed changes have for global climate and societal impacts."

Noting DelSole and Tippett (2009) had recently demonstrated relatively short meteorological records, on the order of 50 years or less, "are not sufficient to detect trends in a mode of variability such as ENSO," Ray and Giese (2012) explored the postulated global warming-ENSO connection by comparing sea surface temperatures (SSTs) derived from an ocean reanalysis with three widely used SST reconstructions. They used the reanalysis data to evaluate potential changes in ENSO characteristics over the period 1871–2008. The two researchers conclude, "there is no evidence that there are changes in the [1] strength, [2] frequency, [3]duration, [4] location or [5] direction of propagation of El Niño and La Niña anomalies caused by global warming during the period from 1871 to 2008."

Yeh *et al*. (2011) state there is an "expectation that ENSO [El Niño-Southern Oscillation] statistics would change under global warming, although the details remain uncertain because of the large spread of model projections for the 21st century (Guilyardi *et al*., 2009)." In addition, they note there is evidence of "increasing intensity as well as occurrence frequency of the so-called Central Pacific (CP) El Niño events since the 1990s." This brings up the question of whether the latter is a consequence of global warming.

In exploring this highly unsettled (Collins *et al*., 2010) situation, Yeh *et al*. ran a multi-millennial CGCM (coupled general circulation model) simulation "to assess whether the natural changes in the frequency of CP El Niño occurrence simulated by the model are comparable to the observed changes over the last few decades," suggesting, "if the changes are similar then we cannot rule out the possibility that the recent changes are simply natural variability."

The five researchers report their control simulation—run for 4.200 years of data with the present values of greenhouse gases—"exhibits large variations of the occurrence frequency of the CP El Niño versus the eastern Pacific (EP) El Niño" and "simulates to some extent changes in the occurrence ratio of CP and EP El Niño in comparison with the observations." Therefore, they conclude, "we cannot exclude the possibility that an increasing of occurrence frequency of CP El Niño during recent decades in the observation could be a part of natural variability in the tropical climate system," providing more evidence for the likely cyclical origin of recent global warming.

Nicholls (2008) notes there has been a "long-running debate as to how the El Niño-Southern Oscillation (ENSO) might react to global warming," and "the focus in most model studies on ENSO and climate change has been on whether the Pacific will tend to a more permanent El Niño state as the world warms due to an enhanced greenhouse effect." Nicholls examined "trends in the seasonal and temporal behaviour of ENSO, specifically its phase-locking to the annual cycle over the past 50 years," where phase-locking "means that El Niño and La Niña events tend to start about April–May and reach a maximum amplitude about December–February," which is why he examined trends in ENSO indices for each month of the year.

The Australian researcher thus determined "there has been no substantial modulation of the temporal/seasonal behaviour of the El Niño-Southern Oscillation"—as measured by the sea surface temperature averaged across the region 5°S–5°N by 120°W–170°W, and the Southern Oscillation Index (the non-standardized difference between sea level pressures at Tahiti and Darwin)—over the past 50 years, during what he describes as "a period of substantial growth in the atmospheric concentrations of greenhouse gases and of global warming." Nicholls reports "the temporal/seasonal nature of the El Niño-Southern Oscillation has been remarkably consistent through a period of strong global warming," clearly repudiating climate-model-derived inferences of global warming increasing both the frequency and intensity of ENSO events.

In a paper addressing "the need for a reliable ENSO index that allows for the historical definition of ENSO events in the instrumental record back to 1871," Wolter and Timlin (2011) state their Multivariate ENSO Index (MEI) was originally defined by them (Wolter and Timlin, 1993, 1998) as "the first seasonally varying principal component of six atmosphere-ocean variable fields in the tropical Pacific basin." This index, they note, "provides for a more complete and flexible description of the ENSO phenomenon than single variable ENSO indices."

To improve even further on their earlier refinement, the two U.S. researchers describe their efforts "to boil the MEI concept down to its most essential components (based on sea level pressure and sea surface temperature) to enable historical analyses that more than double its period of record." Their efforts, they note, were "designed to help with the assessment of ENSO conditions through as long a record as possible to be able to differentiate between 'natural' ENSO behavior in all its rich facets, and the 'Brave New World' of this phenomenon under evolving greenhouse gas-related climate conditions."

Wolter and Timlin report, "the new MEI.ext confirms that ENSO activity went through a lull in the early- to mid-20th century, but was just about as prevalent one century ago as in recent decades." They write, "so far, none of the behavior of recent ENSO events appears unprecedented, including duration, onset timing, and spacing in the last few decades compared to a full century before then."

Evans *et al*. (2002) reconstructed gridded Pacific Ocean sea surface temperatures from coral stable isotope ($\delta^{18}O$) data, from which they assessed ENSO activity over the period 1607–1990. The results of their analysis show a period of relatively vigorous ENSO activity over the colder-than-present period of

1820–1860 was "similar to [that] observed in the past two decades." Similarly, in a study partly based on the instrumental temperature record for the period 1876–1996, Allan and D'Arrigo (1999) found four persistent El Niño sequences similar to that of the 1990s, and using tree-ring proxy data covering the period 1706 to 1977, they found several other ENSO events of prolonged duration. There were four or five persistent El Niño sequences in each of the eighteenth and nineteenth centuries, and both these centuries were significantly colder than the final two decades of the twentieth century. This led them to conclude there is "no evidence for an enhanced greenhouse influence in the frequency or duration of 'persistent' ENSO event sequences."

Brook *et al*. (1999) analyzed the layering of couplets of inclusion-rich calcite over inclusion-free calcite, and darker aragonite over clear aragonite, in two stalagmites from Anjohibe Cave in Madagascar, comparing their results with historical records of El Niño events and proxy records of El Niño events and sea surface temperatures derived from ice core and coral data. The cave-derived record of El Niño events compared well with the historical and proxy ice core and coral records, and these data indicated, Brook *et al*. report, "the period 1700–50 possibly witnessed the highest frequency of El Niño events in the last four and a half centuries while the period 1780–1930 was the longest period of consistently high El Niño occurrences." Both of these periods were considerably cooler than the 1980s and 1990s.

Braganza *et al*. (2009) developed an annually resolved Pacific-basin-wide ENSO index for the period AD 1525–1982 based on tree-ring, coral, and ice-core data obtained from the western equatorial Pacific, New Zealand, the central Pacific, and subtropical North America—which constitute, they write, "a set of multiproxy indicators from locations that span a broader area of the Pacific basin than has been attempted previously." According to the five researchers, "the proxy ENSO index over the last 450 years shows considerable amplitude and frequency modulation in the 3–10 year band on multidecadal time scales." They further state, "in the context of the entire record, we find no pronounced signal of twentieth century climate change in ENSO variability."

Meyerson *et al*. (2003) analyzed an annually dated ice core from the South Pole for the period 1487–1992, focusing on the marine biogenic sulfur species methanesulfonate (MS). They used orthogonal function analysis to calibrate the high-resolution MS series with associated environmental series for the period of overlap (1973–1992). This procedure allowed them to derive a five-century history of ENSO activity and southeastern Pacific sea-ice extent; the latter parameter "is indicative of regional temperatures within the Little Ice Age period in the southeastern Pacific sea-ice sector."

Meyerson *et al*. found a shift toward generally cooler conditions at about 1800 AD. This shift was concurrent with an increase in the frequency of El Niño events in the ice core proxy record, which contradicts what climate models generally predict. Their findings are, by contrast, harmonious with the historical El Niño chronologies of both South America (Quinn and Neal, 1992) and the Nile region (Quinn, 1992; Diaz and Pulwarty, 1994). These records depict, they note, "increased El Niño activity during the period of the Little Ice Age (nominally 1400–1900) and decreased El Niño activity during the Medieval Warm Period (nominally 950–1250)," as per Anderson (1992) and de Putter *et al*. (1998).

Wang *et al*. (2004) evaluated all ENSO events they could identify in existing records of the past 500 years to see if there was any significant increase in their frequency of their occurrence over the twentieth century. Although Wang *et al*. note El Niño frequency was a little higher in the twentieth century, and La Niña frequency was somewhat higher during the Little Ice Age, they report "ENSO frequency [was] relatively stationary during the last 500 years, including the Little Ice Age (1550–1850) and Modern Warming Period (the 20th century)." They note Diaz and Pulwarty (1994) found "the frequency of ENSO during the Little Ice Age does not differ greatly from that found in the 20th century based on singular spectrum analysis and evolutive spectral analysis."

Herweijer *et al*. (2007) put into longer perspective "the famous droughts of the instrumental record (i.e., the 1930s Dust Bowl and the 1950s Southwest droughts)," using Palmer Drought Severity Index data found in the North American Drought Atlas prepared by Cook and Krusic (2004), which were derived from a network of drought-sensitive tree-ring chronologies (some stretching back to AD 800 and encompassing the Medieval Warm Period). The authors found "medieval megadroughts were forced by protracted La Niña-like tropical Pacific sea surface temperatures." In addition, the data identify "a global hydroclimatic 'footprint' of the medieval era revealed by existing paleoclimatic archives from the tropical Pacific and ENSO-sensitive tropical and extratropical land regions." The authors state, "this global pattern matches that observed for modern-day persistent North American drought," namely, "a La Niña-like tropical Pacific."

Khider *et al*. (2011) developed a history of ENSO variability over a period of time that included both the Medieval Climate Anomaly (MCA, AD 800–1300) and the Little Ice Age (LIA, AD 1500–1850) "by comparing the spread and symmetry of $\delta^{18}O$ values of individual specimens of the thermocline-dwelling planktonic foraminifer *Pulleniatina obliquiloculata* extracted from discrete time horizons of a sediment core collected in the Sulawesi Sea, at the edge of the western tropical Pacific warm pool," and by interpreting the spread of individual $\delta^{18}O$ values "to be a measure of the strength of both phases of ENSO." The five researchers used the symmetry of the $\delta^{18}O$ distributions "to evaluate the relative strength/frequency of El Niño and La Niña events." They report "the strength/frequency of ENSO, as inferred from the spread of the $\delta^{18}O$ distributions, during the MCA and during the LIA was not statistically distinguishable and was comparable to that of the 20th century." They write, their results suggest "ENSO during the MCA was skewed toward stronger/more frequent La Niña than El Niño," an observation they note is "consistent with the medieval megadroughts documented from sites in western North America."

Cobb *et al*. (2003) generated multi-century, monthly-resolved records of tropical Pacific climate variability over the last millennium by splicing together overlapping fossil-coral records from the central tropical Pacific. This allowed them "to characterize the range of natural variability in the tropical Pacific climate system with unprecedented fidelity and detail." They discovered "ENSO activity in the seventeenth-century sequence [was] not only stronger, but more frequent than ENSO activity in the late twentieth century." They also found "there [were] 30-yr intervals during both the twelfth and fourteenth centuries when ENSO activity [was] greatly reduced relative to twentieth-century observations." Once again, ENSO activity is shown to have been much greater and more intense during the cold of the Little Ice Age than the warmth of the late twentieth century.

Eltahir and Wang (1999) used water-level records of the Nile River as a proxy for El Niño episodes over the past 14 centuries. Although the frequency of El Niño events over the 1980s and 1990s was high, they found it was not without precedent, being similar to values observed near the start of the twentieth century and much the same as those "experienced during the last three centuries of the first millennium." The latter period, according to Esper *et al*. (2002), was also significantly cooler than the latter part of the twentieth century.

Langton *et al*. (2008) used geochemical data obtained by analysis of a sediment core extracted from the shallow-silled and intermittently dysoxic Kau Bay in Halmahera, Indonesia (1°N, 127.5°E) to reconstruct century-scale climate variability within the Western Pacific Warm Pool over the past 3,500 years. Langton *et al*. report, "basin stagnation, signaling less El Niño-like conditions, occurred during the time frame of the Medieval Warm Period (MWP), from ca. 1000 to 750 years BP," which was "followed by an increase in El Niño activity that culminated at the beginning of the Little Ice Age ca. 700 years BP." Thereafter, their record suggests, "the remainder of the Little Ice Age was characterized by a steady decrease in El Niño activity with warming and freshening of the surface water that continued to the present." In addition, they state, "the chronology of flood deposits in Laguna Pallcacocha, Ecuador (Moy *et al*., 2002; Rodbell *et al*., 1999), attributed to intense El Niño events, shows similar century-scale periods of increased [and decreased] El Niño frequency."

The nine researchers conclude "the finding of similar century-scale variability in climate archives from two El Niño-sensitive regions on opposite sides of the tropical Pacific strongly suggests they are dominated by the low-frequency variability of ENSO-related changes in the mean state of the surface ocean in [the] equatorial Pacific," and the "century-scale variability," as they describe it, suggests global warming typically tends to retard El Nino activity and global cooling tends to promote it.

Woodroffe *et al*. (2003) confirmed this finding applied over an even longer period of time. Using oxygen isotope ratios obtained from *Porites* microatolls at Christmas Island in the central Pacific to provide high-resolution proxy records of ENSO variability since 3.8 thousand years ago (ka), they found, "individual ENSO events in the late Holocene [3.8–2.8 ka] appear at least as intense as those experienced in the past two decades." In addition, "geoarcheological evidence from South America (Sandweiss *et al*., 1996), Ecuadorian varved lake sediments (Rodbell *et al*., 1999), and corals from Papua New Guinea (Tudhope *et al*., 2001) indicate that ENSO events were considerably weaker or absent between 8.8 and 5.8 ka," the warmest period of the Holocene. They report, "faunal remains from archeological sites in Peru (Sandweiss *et al*., 2001) indicate that the onset of modern, rapid ENSO recurrence intervals was achieved only after ~4-3 ka," or during the long cold interlude that preceded the Roman Warm Period (McDermott *et al*., 2001).

Wei *et al*. (2007) reconstructed three mid-Holocene sea surface temperature (SST) records spanning more than 30 years using Sr/Ca ratios derived from cores of three *Porites lutea* colonies in the fringe reef at Dadonghai, Sanya in southern Hainan Island, which lived about 6,000 years ago at a water depth similar to that of modern coral at that location (approximately 18°12'N, 109°33'E). According to the six researchers, "the results indicate warmer than present climates between circa 6100 yr B.P. and circa 6500 yr B.P. with the mid-Holocene average minimum monthly winter SSTs, the average maximum monthly summer SSTs, and the average annual SSTs being about 0.5°–1.4°C, 0°–2.0°C, and 0.2°–1.5°C higher, respectively, than they were during 1970–1994." In addition, they report, "ENSO variability in the mid-Holocene SSTs was weaker than that in the modern record, and the SST record with the highest summer temperatures from circa 6460 yr B.P. to 6496 yr B.P. shows no robust ENSO cycle."

McGregor and Gagan (2004) used several annually resolved fossil *Porites* coral $\delta^{18}O$ records to investigate the characteristics of ENSO events over a period of time in which Earth cooled substantially. For comparison, study of a modern coral core provided evidence of ENSO events for the period 1950–1997, the results of which analysis suggest they occurred at a rate of 19 events/century. The mid-Holocene coral $\delta^{18}O$ records, by contrast, showed reduced rates of ENSO occurrence: 12 events/century for the period 7.6–7.1 ka, eight events/century for the period 6.1–5.4 ka, and six events/century at 6.5 ka. For the period 2.5–1.7 ka, the results were quite different, with all of the coral records revealing "large and protracted $\delta^{18}O$ anomalies indicative of particularly severe El Niño events." They note, for example, "the 2.5 ka Madang PNG coral records a protracted 4-year El Niño, like the 1991–1994 event, but almost twice the amplitude of [the] 1997–1998 event (Tudhope *et al*., 2001)." In addition, "the 2 ka Muschu Island coral $\delta^{18}O$ record shows a severe 7-year El Niño, longer than any recorded Holocene or modern event." And they add, "the 1.7 ka *Porites* microatoll of Woodroffe *et al*. (2003) also records an extreme El Niño that was twice the amplitude of the 1997–1998 event." Taken together, these results portray a "mid-Holocene El Niño suppression and late Holocene amplification."

That there tend to be fewer and weaker ENSO events during warm periods is documented further by Riedinger *et al*. (2002). In a 7,000-year study of ENSO activity in the vicinity of the Galapagos Islands, they determined "mid-Holocene [7130 to 4600 yr BP] El Niño activity was infrequent," when global air temperature was significantly warmer than it is now, but both the "frequency and intensity of events increased at about 3100 yr BP," when the world cooled below today's temperatures. Throughout the former 2,530-year warm period, there were only 23 strong to very strong El Niños and 56 moderate events, according to their data, whereas throughout the most recent (and significantly colder) 3,100-year period, they identified 80 strong to very strong El Niños and 186 moderate events. These numbers correspond to rates of 0.9 strong and 2.2 moderate occurrences per century in the earlier, warm period and 2.7 strong and 6.0 moderate occurrences per century in the latter, cool period, an approximate tripling of the rate of occurrence of both strong and moderate El Niños in going from the warmth of the Holocene "Climatic Optimum" to the colder conditions of the past three millennia.

Similar results have been reported by Andrus *et al*. (2002), who found sea surface temperatures off the coast of Peru were 3 to 4°C warmer 6,000 years ago than in the 1990s and provided little evidence of El Niño activity.

Moy *et al*. (2002) analyzed a sediment core from lake Laguna Pallcacocha in the southern Ecuadorian Andes, producing a proxy measure of ENSO over the past 12,000 years. For the moderate and strong ENSO events detected by their analytical techniques (weaker events are not registered), "the overall trend exhibited in the Pallcacocha record includes a low concentration of events in the early Holocene, followed by increasing occurrence after 7,000 cal. yr BP, with peak event frequency occurring at ~1,200 cal. yr BP," after which the frequency of events declines dramatically to the present, they write.

In the last 1,200 years of this record, the decline in the frequency of ENSO events is anything but smooth. In coming out of the Dark Ages Cold Period, one of the coldest intervals of the Holocene (McDermott *et al*., 2001), the number of ENSO events drops by an order of magnitude, from a high of approximately 33 events per 100 yr to a low of about three events per 100 yr, centered approximately on the year AD 1000, right in the middle of the Medieval Warm Period as delineated by the work of Esper *et al*.

(2002). At approximately AD 1250, the frequency of ENSO events exhibits a new peak of approximately 27 events per century in the midst of the longest sustained cold period of the Little Ice Age, again as delineated by the work of Esper *et al*. Finally, ENSO event frequency declines in zigzag fashion to a low on the order of four to five events per century at the start of the Current Warm Period, which according to the temperature history of Esper *et al*. begins at about 1940.

A similar decline in ENSO events during the Medieval Warm Period is noted by Rein *et al*. (2004), who derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin on the edge of the Peruvian shelf about 80 km west of Lima, Peru. Rein *et al*. found a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the late Medieval period. They report "lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250." They write, "all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly."

In addition, they report, "this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain." Rein *et al*. note, for example, "from an Ecuadorian lake record where moderate to strong El Niño floods are recorded (Moy *et al*., 2002), a minimum of such events is reported during the upper Medieval period." They also note the oldest (A.D. 928–961) of the five "time windows" on central Pacific El Niño activity provided by the corals investigated by Cobb *et al*. (2003) exhibits evidence for weaker El Niños than all subsequent time windows extending to 1998. In addition, they note, "extreme long-lasting droughts that peaked coincident with those in the Peru record around A.D. 1160, are reported from several archives in the western USA and Southern Patagonia (Stine, 1994)," and near-contemporaneous dry periods "also occurred in the tropical Andes (Abbot *et al*., 1997; Binford *et al*., 1997), Oman (Fleitmann *et al*., 2003) and eastern Africa (De Putter *et al*., 1998; Verschuren *et al*., 2000)." They conclude, "hints that these droughts are not only coinciding events but related to El Niño anomalies come from the high-resolution Moon Lake (North Dakota, USA) salinity record (Laird *et al*., 1996)."

Rittenour *et al*. (2000) studied a recently revised New England varve chronology derived from proglacial lakes formed during the recession of the Laurentide ice sheet some 17,500 to 13,500 years ago, finding "the chronology shows a distinct interannual band of enhanced variability suggestive of El Niño-Southern Oscillation (ENSO) teleconnections into North America during the late Pleistocene, when the Laurentide ice sheet was near its maximum extent ... during near-peak glacial conditions." But during the middle of the Holocene, when it was considerably warmer, Overpeck and Webb (2000) report data from corals suggest "interannual ENSO variability, as we now know it, was substantially reduced, or perhaps even absent."

Nederbragt and Thurow (2005) analyzed the varve thickness profiles of two sediment cores retrieved from the Santa Barbara Basin off the coast of California, USA, to determine how the strength of the El Niño/Southern Oscillation (ENSO) phenomenon has varied there over the past 15,000 years. The records show the strength of the ENSO signal fluctuated on multidecadal to centennial timescales. In spite of this variability, Nederbragt and Thurow note power spectra analysis gave no indication of a unidirectional trend in either the frequency or amplitude of ENSO events. The ENSO signal at millennial timescales was reported to be "more or less constant."

In a follow-up to their 2004 work (Rein *et al*., 2004), Rein *et al*. (2005) developed high-resolution marine proxy data for El Niño variability over the last 20,000 years, obtained by analyzing a sediment core retrieved from a sheltered basin on the edge of the Peruvian shelf (12°03'S, 77°39.8'W) about 80 km west of Lima. The most well-defined feature of the record was a dramatic depression of El Niño activity between about 5.6 and 8 thousand years ago, which coincided with the major warmth of the Holocene Climatic Optimum. The next-most significant feature was "the medieval period of low El Niño activity," which the researchers describe as "the major anomaly during the late Holocene"—i.e., the Medieval Warm Period—as their data indicate "El Niños were persistently weak between 800 and 1250 AD."

Studying the past millennium in more detail, Rein *et al.* found signs of just the opposite behavior, though on a much shorter timescale: On average, they note, "temperature reconstructions show higher temperatures with increased El Niño activity." That finding was to be expected, however, for that is what El Niños do—they create significant spikes in mean global air temperature, as was dramatically demonstrated by the 1997–1998 El Niño that produced the highest mean annual temperature (1998) of the entire satellite record and gave the record its slightly upward-trending slope. Although El Niños may significantly impact short-term climate, periodically nudging global temperatures upward, they in turn are even more strongly affected by long-term climate, as demonstrated by the findings discussed in the preceding paragraphs of this section, where it is readily seen long-term warmth depresses El Niño activity.

In providing some additional examples of this phenomenon—the overriding power of centennial- to millennial-scale climate variability compared to decadal to multidecadal variability (in terms of what drives what when it comes to changes in temperature and El Niño activity)—Rein *et al*. report, during the Medieval Warm Period, when "Northern Hemisphere temperatures peaked," there was "extraordinarily weak El Niño activity"; in the late thirteenth and early seventeenth centuries, "temperatures in the Northern Hemisphere were rather cool but El Niño activity was high"; and during the nineteenth century, when the Northern Hemisphere began to warm as the planet commenced its recovery from the global chill of the Little Ice Age, El Niño activity began to decline, as Medieval-Warm-Period-like conditions were once again being established as the Current Warm Period was coming into existence.

In light of these observations, it is quite likely the slight global warming evident in the satellite record of the past three decades was simply a natural consequence of El Niño activity, which will likely subside somewhat as the Current Warm Period (which we contend to be primarily a product of Earth's natural millennial-scale oscillation of climate) becomes more firmly entrenched at a slightly higher temperature commensurate with that of the Medieval Warm Period.

Another explanation may rest in the work of Verdon and Franks (2006), who used "proxy climate records derived from paleoclimate data to investigate the long-term behavior of the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO)" over the past 400 years. The pair of researchers found climate shifts associated with changes in the PDO "occurred with a similar frequency to those documented in the 20th century." In addition, and more importantly, they find "phase changes in the PDO have a propensity to coincide with changes in the relative frequency of ENSO events, where the positive phase of the PDO is associated with an enhanced frequency of El Niño events, while the negative phase is shown to be more favourable for the development of La Niña events."

The two Australian scientists note the numerous El Niño events of the recent past "have been reported as unusual, and have even been suggested to be possible evidence of anthropogenic climate change [e.g., Trenberth and Hoar, 1996]." However, they continue, "the paleo records suggest that the apparent lack of La Niña events and high frequency of El Niño events over the past two decades may not be abnormal and could be attributed to the fact that during this time the PDO has been in a positive phase," such that "when the PDO switches back to a negatively dominated phase, it is quite likely that the frequency of La Niña events will increase once again." Consequently, there is no compelling reason to conclude the recent preponderance of El Niño events over La Niña events is a "fingerprint" of CO_2-induced global warming, especially in light of the evidence highlighted in this section.

Davies *et al*. (2012) note, "variations in the frequency and amplitude of the El Niño-Southern Oscillation (ENSO) recorded in both instrumental and paleoclimate archives have led to speculation that global warming may cause fundamental changes in this preeminent mode of global interannual climate variability (Fedorov and Philander, 2000)." They note there is speculation "warmer climates may promote a permanent El Niño state (Wara *et al*., 2005; Fedorov *et al*., 2006)." In a study designed to explore this possibility further, Davies *et al*. analyzed the latest Cretaceous laminated Marca Shale of California, which permits "a seasonal-scale reconstruction of water column flux events and, hence, interannual paleoclimate variability," during what is known to have been a "past 'greenhouse' climate state."

The four researchers report "significant spectral peaks obtained from lamina-derived time series analysis of the Marca Shale closely resemble those of modern and historical ENSO variability." In addition, "the parameters from which the time series are derived (biogenic- and terrigenous-lamina thickness and bioturbation index) appear directly related to the marine production and flux, incursion of oxygenated waters, and input of terrigenous sediment that would be influenced by ENSO-type mechanisms of inter-annual variability." Davies *et al*. say there is "little support for the existence of a 'permanent El Niño' in the Late Cretaceous, in the sense of the continual El Niño state depicted by Fedorov *et al*. (2006)." They say this evidence "builds on results from the Cretaceous Arctic (Davies *et al*., 2011) and from younger Eocene and Miocene warm periods (Huber and Caballero, 2003; Galeotti *et al*., 2010; Lenz *et al*., 2010) to emphasize that there was robust ENSO variability in past 'greenhouse' episodes and that future warming will be unlikely to promote a permanent El Niño state."

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4.3.2 Influence on Extreme Weather Events

Computer model simulations have given rise to concerns that weather-related disasters will be exacerbated under warm, El Niño conditions. The validity of this assertion is challenged by the studies reported in this section, which demonstrate ENSO events generally do not lead to greater frequency or severity of extreme weather events.

Changnon (1999) determined adverse weather events attributed to the El Niño of 1997–1998 cost the United States economy $4.5 billion and contributed to the loss of 189 lives, which is serious indeed. On the other hand, he determined El Niño-related benefits amounted to approximately $19.5 billion—resulting primarily from reduced energy costs, industry sales, and reduction in hurricane damage—and a total of 850 lives were saved, thanks to the reduction of bad winter weather. Thus the net impact of the 1997–1998 El Niño on the United States, Changnon writes, was "surprisingly positive," in stark contrast to what was often reported in the media and by climate alarmists, who tended, in his words, "to focus only on the negative outcomes."

Another "surprisingly positive" consequence of El Niños is their tendency to moderate the frequency and intensity of Atlantic hurricanes. Working with data for 1950–1998, Wilson (1999) determined the probability of having three or more intense hurricanes during a warmer El Niño year was approximately 14 percent, and during a cooler non-El Niño year the probability jumped to 53 percent. Similarly, in a study of tropical storm and hurricane strikes along the southeast coast of the United States over the entire last century, Muller and Stone (2001) determined "more tropical storm and hurricane events can be anticipated during La Niña seasons [3.3 per season] and fewer during El Niño seasons [1.7 per season]."

In another study of Atlantic basin hurricanes, this one considering the period 1925 to 1997, Pielke and Landsea (1999) report average hurricane wind speeds during warmer El Niño years were about six meters per second lower than during cooler La Niña years. In addition, they report hurricane damage during cooler La Niña years was twice as great as during warmer El Niño years. These year-to-year variations indicate hurricane frequency and intensity—as well as damage—tend to decline under warmer El Niño conditions, just the opposite of the impression typically conveyed to the public.

In the North Indian Ocean, Singh *et al*. (2000) studied tropical cyclone data pertaining to the period 1877–1998, finding tropical cyclone frequency declined there during the months of most severe cyclone formation (November and May), when ENSO was in a warm phase. Similarly, De Lange and Gibb (2000) studied New Zealand storm surges recorded by several tide gauges in Tauranga Harbor over the period 1960–1998, finding a considerable decline in both the annual number of such events and their magnitude in the latter (warmer) half of the nearly four-decade record, noting La Niña seasons typically experienced more storm surge days than El Niño seasons. Regarding Australia, Kuhnel and Coates (2000) found yearly fatality event-days due to floods, bushfires, and heatwaves in 1876–1991were greater in cooler La Niña years than in warmer El Niño years.

In a study of breeding populations of Cory's Shearwaters on the Tremiti Islands of Italy, Brichetti *et al*. (2000) found survival rates of the birds during El Niño years were greater than during La Niña years, which they attribute to the calming influence of El Niño on Atlantic hurricanes.

Elsner *et al*. (2001) used annual U.S. hurricane data obtained from the U.S. National Oceanic and Atmospheric Administration, plus data obtained from the Joint Institute for the Study of the Atmosphere and the Oceans for average sea surface temperature (SST) anomalies for the region bounded by 6°N to 6°S latitude and 90°W to 180°W longitude (the "cold tongue index" or CTI) to discover whether there was a connection between the number of hurricanes that hit the eastern coast of the United States each year and the presence or absence of El Niño conditions. Based on data for the period 1901–2000, they found "when CTI values indicate below normal equatorial SSTs, the probability of a U.S. hurricane increases." Or as they describe the relationship in another place, "the annual count of hurricanes is higher when values of the CTI are lower (La Niña events)." Thus the entire past century of real-world hurricane experience indicates the yearly number of U.S. land-falling hurricanes has tended to decrease during El Niño conditions, as has the overall occurrence of hurricanes in the Atlantic basin.

Schwartz and Schmidlin (2002) examined past issues of *Storm Data*—a publication of the U.S. National Weather Service (NWS)—to compile a blizzard database for the years 1959–2000 for the conterminous United States. They analyzed the data to determine temporal trends and spatial patters of U.S. blizzards, as well as their relationship to ENSO. Over the 41-year period of their study, they identified 438 blizzards, an average of 10.7 blizzards per year. Year-to-year blizzard variability was significant, however, with the number of annual blizzards ranging from a low of one in the winter of 1980–1981 to a high of 27 during the 1996–1997 winter. In addition, a weak but marginally significant relationship with ENSO was noted, with a tendency for two to three more blizzards to occur during La Niña winters than during El Niño winters.

Hudak and Young (2002) used an objective method of identifying June through November storms in the southern Beaufort Sea based on surface wind speed over the period 1970–1995, finding considerable year-to-year variation in the number of storms but no discernible trend. They also observed a small increase in the number of storms during El Niño vs. La Niña years, but they report "due to the relatively small number of cases, no statistical significance can be associated with this difference." Thus, in a region of the world where climate models predict the effects of CO_2-induced global warming should be most evident, the past quarter-century has seen no change in the number of June-November storms.

Higgins *et al*. (2002) examined the influence of two important sources of Northern Hemispheric climate variability—ENSO and the Arctic Oscillation (AO)—on winter (Jan–Mar) daily temperature extremes throughout the conterminous United States over the 50-year period 1950–1999. This work revealed considerable decadal variability in surface air temperatures. Nevertheless, during El Niño years the number of extreme temperature days was found to decrease by around 10 percent, and during La Niña years they increased by around 5 percent. They found little or no difference in the number of extreme temperature days between the AO's positive and negative phases.

Goddard and Dilley (2005) state the huge reported "cost" of El Niño events "contributes greatly to misconceptions about the global climate effects and socioeconomic impacts of El Niño and La Niña." They note the monetary figures typically bandied about represent a gross estimate of all hydrometeorological impacts worldwide in specific El Niño years, but they note "how these losses compare with those during ENSO-neutral periods has not been established," adding, "during El Niño events, El Niño is implicitly assumed to be associated with all climate-related losses." They thus embarked on a study intended to provide the missing information.

Goddard and Dilley arrive at three major conclusions. First, they conclude "perturbation to precipitation over land areas is only weakly affected by ENSO extremes," as they found "the risk of widespread extreme precipitation anomalies during ENSO extremes is comparable to that during neutral conditions" and "the highest values of integrated rainfall perturbation are not greater during ENSO extremes than during neutral conditions." Second, they found "the frequency of reported climate-related disasters does not increase during El Niño/La Niña years relative to neutral years." And third, they found seasonal rainfall forecast skill increases "in magnitude and coverage, during ENSO extremes," such that "the prudent use of climate forecasts could mitigate adverse impacts and lead instead to increased beneficial impacts, which could transform years of ENSO extremes into the least costly to life and property."

Among the beneficial impacts of ENSO extremes Goddard and Dilley say could yield a more complete appreciation of the differing socioeconomic impacts of El Niño and La Niña events is the well-established fact that "tropical Atlantic hurricanes that threaten the southeastern United States, the Caribbean, and eastern Central America occur less frequently during El Niño years (Gray, 1984)." Moreover, "warmer winter temperatures commonly are observed in the northern United States during El Niño, leading to less energy use and, therefore, lower energy prices (Chagnon, 1999)."

Goddard and Dilley conclude, "between mitigating adverse climate effects and taking advantage of beneficial ones through the prudent use of climate forecasts, El Niño and La Niña years may eventually result in substantially lower socioeconomic losses, globally, than are realized in other years." Even in the absence of such actions, their work (and that of many other researchers) reveals there is little to fear during extreme ENSO years as compared to ENSO-neutral years.

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5

Observations: The Cryosphere

Donald J. Easterbrook (USA)

Clifford D. Ollier (Australia)

Robert M. Carter (Australia)

Key Findings

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Key Findings

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice in glaciers, icecaps, and sea ice. Worries about untoward melting of the cryosphere in response to carbon dioxide-forced temperature rise have existed since the earliest days of global warming alarm in the 1980s.

- Satellite and airborne geophysical datasets used to quantify the global ice budget are short and the methods involved in their infancy, but results to date suggest both the Greenland and Antarctic Ice Caps are close to balance.

- Deep ice cores from Antarctica and Greenland show climate change occurs as both major glacial-interglacial cycles and as shorter decadal and centennial events with high rates of warming and cooling, including abrupt temperature steps.

- Observed changes in temperature, snowfall, ice flow speed, glacial extent, and iceberg calving in both Greenland and Antarctica appear to lie within the limits of natural climate variation.

- Global sea-ice cover remains similar in area to that at the start of satellite observations in 1979, with ice shrinkage in the Arctic Ocean since then being offset by growth around Antarctica.

- During the past 25,000 years (late Pleistocene and Holocene) glaciers around the world have fluctuated broadly in concert with changing climate, at times shrinking to positions and volumes smaller than today.

- This fact notwithstanding, mountain glaciers around the world show a wide variety of responses to local climate variation, and do not respond to global temperature change in a simple, uniform way.

- Tropical mountain glaciers in both South America and Africa have retreated in the past 100 years because of reduced precipitation and increased solar radiation; some glaciers elsewhere also have retreated since the end of the Little Ice Age.

- The data on global glacial history and ice mass balance do not support the claims made by the IPCC that CO_2 emissions are causing most glaciers today to retreat and melt.

- No evidence exists that current changes in Arctic permafrost are other than natural or that methane released by thawing would significantly affect Earth's climate.

- Most of Earth's gas hydrates occur at low saturations and in sediments at such great depths below the seafloor or onshore permafrost that they will barely be affected by warming over even one thousand years.

Introduction

The cryosphere comprises those places on or near Earth's surface so cold that water is present in solid form as snow or ice. The cryosphere forms the frozen part of the larger hydrosphere, which encompasses all the water contained in rain, rivers, lakes, and oceans. The processes and characteristics of the cryosphere and hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, the hydrosphere and cryosphere also change in response to external climate change forcings, some of which may be natural (e.g., changed solar insolation) and some of human origin (e.g., industrial greenhouse gas forcing). This distinction, which applies to all aspects of Earth's climate system, is easy to draw in principle, but in practice it has proved difficult to establish that any specific changes in the cryosphere or hydrosphere documented over the past century have their origins in human activity.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC) commented, "recent decreases in ice mass are correlated with rising surface air temperatures. This is especially true in the region north of 65°N, where temperatures have increased by about twice the global average from 1965 to 2005" (IPCC 2007, p. 339). The IPCC went on to report decreased snow cover "in most regions, especially in spring and summer," freeze-up dates in the Northern Hemisphere occurring later, breakup dates occurring earlier, declines in sea-ice extent, and similar findings. All of these statements were made against the background assumption that the warming was of anthropogenic origin.

The authors of the 2009 report of the Nongovernmental International Panel on Climate Change (NIPCC) and its 2011 interim report contended many of the IPCC's findings on this subject were incorrect, resulting from the inappropriate use of circumstantial evidence, cherry-picking of data, or misrepresentation of available research. Specifically, Idso and Singer (2009, p. 4) reported:

> Glaciers around the world are continuously advancing and retreating, with a general pattern of retreat since the end of the Little Ice Age. There is no evidence of an increased rate of melting overall since CO_2 levels rose above their pre-industrial levels, suggesting CO_2 is not responsible for glaciers melting.
>
> Sea ice area and extent have continued to increase around Antarctica over the past few decades. Evidence shows that much of the reported thinning of Arctic sea ice that occurred in the 1990s was a natural consequence of changes in ice dynamics caused by an atmospheric regime shift, of which there have been several in decades past and will likely be several in the decades to come, totally irrespective of past or future changes in the air's CO_2 content. The Arctic appears to have recovered from its 2007 decline.

By themselves such facts as melting glaciers and Arctic sea ice, while interesting, tell one nothing about causation. Any significant warming, whether anthropogenic or natural, will melt ice. To claim anthropogenic global warming (AGW) is occurring based on such information is to confuse the consequences of warming with its cause, constituting an error in logic. Similar arguments apply also to fluctuations in glacier mass, sea ice, precipitation, and sea level, all of which can be forced by many factors other than temperature change. It is entirely inappropriate to use this type of circumstantial evidence to claim allegedly dangerous human-caused warming is occurring.

This chapter builds on the earlier NIPCC conclusions, bringing up to date our summary of the extensive scientific literature on global warming as it might affect the cryosphere. We again find changes in glacier and sea-ice extent frequently occur in ways that contradict, and rarely reinforce, the claims of the IPCC and the projections of its climate models. Overall, new research conducted since 2007 reinforces NIPCC's 2009 interim summary and finds less melting of ice in the Arctic, Antarctic, and mountain glaciers than previously feared, and no melting at all that could be uniquely attributed to rising carbon dioxide levels.

Some of the key concepts of cryospheric science that are relevant to the climate change issue are presented in the remainder of this introduction to set the stage for the analysis that follows.

GLACIER MASS BALANCE

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation (snowfall) dominates in winter, ablation (melting, avalanching, calving) in summer. If the two are equal, the net mass balance of a glacier or icecap is zero and its snout or periphery will remain stable; otherwise, a glacier will grow in size (advance) if accumulation is the greater (positive mass balance) or shrink and retreat if ablation is the greater (negative mass balance). In this way, climatic factors control glacial behavior, changes in which can be used as indicators of changing climatic conditions over time.

MEASUREMENTS OF MODERN MASS BALANCE

Little data exists with which to accurately quantify glacial mass balance prior to the twenty-first century. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment); and ICESat (Ice Cloud and Land Elevation Satellite)— are in their infancy and often of doubtful accuracy, not least because of the complexity of the data processing needed to correct and interpret the data sets. Also, the data sets are so short they inevitably fail to capture the full range of climatic multidecadal variability.

Correction of satellite data requires an accurate model of the shape of Earth as represented by a spheroidal Terrestrial Reference Frame (TRF). The inadequacy of current TRFs is acknowledged by the Jet Propulsion Laboratory (NASA), which plans to launch a Geodetic Reference Antenna in Space (GRASP) satellite in order to establish a more accurate TRF. Until the accuracy of the TRF has been improved in this or other ways, spaceborne geophysical studies of ice-sheet mass balance and sea-level change will remain uncertain.

ICE CORES

The ice sheets of Greenland and Antarctica contain a remarkable layered ice record of past climatic change back to 120,000 and almost 1 million years ago, respectively. Changing oxygen isotope ratios in the ice act as a proxy for ancient air temperature change; analysis of trapped gases allows the estimation of the CO_2 and CH_4 content of the former atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric physico-chemical parameters also can be determined.

The ice cores show the climate record is permeated by both gradual and rapid change. This includes not only the major glacial-interglacial cycles, but also abrupt climate swings with high short-term rates of warming and cooling. Pleistocene and Holocene fluctuations in glacial activity onland match the climatic events represented in ice cores (and correlative deep sea mud cores), establishing the fidelity of core data as a record of past climatic change.

A particularly important result from ice core studies is the observation that changes in ancient CO_2 lag the equivalent changes in temperature by up to a thousand years, so CO_2 increase cannot be the cause of the warmings documented in the cores.

RECENT HISTORIC EVIDENCE

Glaciers have advanced and retreated during alternating warm and cool climatic periods thoughout geological history. Since the mid-nineteenth century, the overall trend is that glaciers have lost mass as the Earth warmed after the Little Ice Age (LIA). No "unprecedented warming" has occurred during the twentieth century. Many glaciers retreated strongly during the 1915–1945 warm period before major industrial CO_2 emissions, advancing again during the 1945–1977 cool period when CO_2 emissions were soaring. This is precisely the opposite of what would have happened if human-related CO_2 emissions caused enhanced warming and melting.

ANTARCTICA

Antarctica covers 14 million km^2 in area, is 98 percent covered by glacial ice that averages 2.4 km in thickness, corresponds to 90 percent of the world's ice, and represents about 70 percent of the world's fresh water. Melting all Antarctic ice would raise sea level by about 72 m. The average daily temperatures at the South Pole and Vostock, respectively, are -49.4° C and -55.1° C. In order to melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0° C. This is not happening now, nor is it likely to happen soon. The main (east) Antarctic ice sheet has been cooling since 1957 and ice accumulation is increasing rather than decreasing. For the same period, since 1957, warming and ice melting have occurred along the West Antarctic Peninsula, which represents 13 percent of Antarctic Ice. This melting may have an oceanographic rather than a meteorological cause.

So far as we are able to measure it accurately, the Antarctic ice mass is effectively stable on the short historic (meteorological) time scale. On the longer-term climatic scale, Antarctic and nearby ice volume has fluctuated in parallel with millennial-scale climate variability, including ice shrinkage during the Medieval Warm Period to positions that have not been attained again today.

Three facts confirm the likely modern stability of the East Antarctic Ice Sheet: (1) the late twentieth century global warming expected to melt the icecap lay well within the bounds of natural variation and has now ceased; (2) were warming to resume, the probable regional response would be enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; and (3) despite the past few interglacials being up to 5^{O} C warmer than was the Holocene, sediment cores adjacent to Antarctica provide no evidence for any dramatic breakups of the WAIS over the past few glacial cycles.

GREENLAND

The Greenland ice sheet is the second largest ice mass in the world, being 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km^2. The mean altitude of the ice surface is 2,135 m and the ice is nearly 3 km thick in central Greenland. Nonetheless, this represents only a small part (8 percent) of global ice volume and 7 m of sea-level equivalent. During the last glaciation 20,000 years ago, the Greenland massif was part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Although temperatures in Greenland rose during the late twentieth century, they did not rise as fast or as high as they did during the previous natural warming in the 1920s–1930s. Further-more, the temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years, indicating recent warmth is not unprecedented and not necessarily caused by rising CO_2.

The Little Ice Age in Greenland lasted to 1918, helping to achieve a subsequent rate of warming there for 1918–1935 that was 70 percent greater than the rate of warming for 1978–2004. The mean rate-of-rise in atmospheric CO_2 during this period was almost five times greater during the more recent warming.

Recent satellite-borne geophysical measure-ments suggest Greenland, like Antarctica, is in a state of approximate mass balance, quite contrary to the alarmist tone of much public commentary. Modern changes in glacier activity or volume in Greenland have no necessary or likely relation-ship with anthropogenic global warming and are more probably natural.

OTHER ARCTIC GLACIERS

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO_2-induced global warming.

Abundant field evidence shows high Arctic glaciers did not uniformly waste away during the late twentieth century and changed precipitation was as common a cause of glacial change as was changed temperature. As some glaciers advanced, others retreated; in addition, a Jan Mayen Glacier advance was accompanied by warming rather than cooling.

To the degree glaciers present in particular regions have retreated over the past 150 years (e.g., the Canadian Arctic), this is no more than would be expected for glaciers emerging from the Little Ice Age and does not require CO_2 emissions as an additional explanation.

MOUNTAIN GLACIERS

Montane ice is a volumetrically trivial part of the cryosphere (0.6 percent) and represents just 45 cm of sea-level equivalent. Nonetheless, changes in mountain glaciers are important in human terms because the well-watered alpine meadows that occur down-valley from glacier termini have long attracted settlers, and because rivers emanating from glacial valleys are an important wider water resource.

Few quantitative observations of mountain glaciers exist prior to 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Over the past millennium, glaciers have advanced and retreated multiple times as Earth passed successively through the Medieval Warm Period, Little Ice Age, and twentieth century warming. For many of the glaciers that show twentieth century retreat, shrinkage generally started in the late nineteenth century, many decades before human-related CO_2 emissions could have been a factor.

Research on mountain glaciers worldwide has failed to provide evidence for unnatural glacial retreat in the late twentieth century forced by human carbon dioxide emissions. Instead, historic glacial change correlates with the de Vries (~208 year) and Gleissberg (~80 year) solar cycles or fluctuates in sympathy with multidecadal oscillations like the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO).

TROPICAL GLACIERS

African mountain glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights. Repeated allegations have been made that the icecap on Kenya's iconic Mt. Kilimanjaro is melting away because of human-caused global warming.

Similar glacier retreat has been occurring throughout the tropics since the late nineteenth century, including on Mts. Kilimanjaro, Kenya, and Rwenzori in Africa and glaciers in Peru and Bolivia. Studies show reduced precipitation and increased solar radiation (due to decreasing cloudiness) have been the dominant factors influencing ice wastage, which commenced long before human-related CO_2 emissions could have been the cause. Despite common assertions, warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

ARCTIC SEA ICE

It is often claimed that CO_2-induced global warming is melting sea ice, especially in the Arctic Ocean. Semi-permanent oceanic sea ice exists today near the North Pole, but fringing sea ice is an annual, seasonal feature in both the Arctic and around Antarctica. Such ice is susceptible to fast advance or retreat, depending upon local oceanographic and atmospheric conditions. Major sea-ice changes are not uncommon and not necessarily a result of temperature change; often, pulses of warm ocean water or atypical wind motions play a greater role.

Historical records demonstrate Arctic sea ice has fluctuated in sympathy with past multidecadal cycles in temperature, including shrinking to an area similar to that of the 2007 minimum during periods of relative warmth in the 1780s and 1940s; the pattern is that of the well-known multidecadal climate rhythms such as the Atlantic Oscillation and the Arctic and Arctic Ocean Oscillations. Earlier still, about 8,000 years ago during the Holocene Climatic Optimum, temperatures up to 2.5^{O} C warmer than today resulted in what was probably an almost ice-free Arctic Ocean.

Arctic sea-ice cover varies dramatically and naturally over quite short periods of time, and Arctic fauna and flora, including the iconic polar bear, are adapted to deal with the environmental exigencies that result. It has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or a human economic perspective. No convincing research study demonstrates the level of sea-ice in the Arctic Ocean stood at some "ideal" level prior to the Industrial Revolution.

ANTARCTIC SEA ICE

Satellite-mounted sensors document a growth in both pack ice and fast ice across the East Antarctic region since 1979. Between 1979 and 2008, sea ice increased in area by about half a million square kilometers: a 2–3 percent increase during winter and spring and a 5–7 percent increase during summer. Thus the recent trend toward decreasing sea ice in the Arctic since 1979 has been counterbalanced by increasing sea ice in Antarctica, for a net result of little overall change in global sea-ice area.

This result is not consistent with the climate models that project high latitude warming and decreases in polar sea-ice in both hemispheres.

LATE PLEISTOCENE AND HOLOCENE CHANGE

Geological studies establish that before and during the last deglaciation (between 15,000 and 11,500 years ago), multiple, intense, and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. An intrinsic variability of about 1,500 years, termed the Dansgaard-Oeschger rhythm, exhibits a magnitude and intensity up to 20 times greater than warming over the past century.

Similar climatic rhythms continued over the Holocene (last 11,700 years), as seen in the record from Greenland ice cores. The four most important characteristics of the documented variability are: the presence of a temperature peak about 2.5° C warmer than today at ~8,000 y BP; a general cooling trend thereafter; the punctuation of the record by 1,500-year-long, alternating rhythms of warmer and colder climate (termed Bond Cycles, and probably of solar origin), the warm peaks of which exceeded late twentieth century warmth; and for more than 90 percent of the past 10,000 years temperature has been 1–3°C warmer than today.

THE CRYOSPHERE THROUGH DEEP TIME

The total amount of ice in the cryosphere varies from time to time in sympathy with Earth's always-changing climate. Sixty million years ago, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in both the Antarctic and Greenland began after 45 million years ago, although it was probably only about 10 million years ago that a major northern icecap started to accumulate. Global cooling from 3 million years ago onward resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene ice ages.

Throughout this process of high-latitude ice-cap growth, the precise location and size of ice masses worldwide depended upon the vicissitudes of both local and global climate. Never, for any significant period of time, was a stable, global "ice mass balance" attained. Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will again vary in sympathy.

There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation, Nor is there any scientific basis for the common, implicit assump-tion that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

CONTEXT FOR THE MODERN CRYOSPHERE

The geological record of past climate provides an essential context largely missing from discussions about modern ice- volume changes and their significance. The rate and magnitude of twentieth century warming were small compared to the magnitude of the profound natural climate reversals that have occurred over the past 20,000 years. Most importantly, too, none of the documented late Pleistocene and Holocene climatic events was accompanied by significant parallel change in atmospheric levels of carbon dioxide. Furthermore, the rate of glacier retreat has not increased over the period of large increases in CO_2 emissions over the past 60 years.

The data on global glacial history and ice mass balance simply do not support the claims made by the IPCC that CO_2 emissions are causing most glaciers today to retreat and melt. Instead, the null hypothesis—that twentieth century warming reflected natural climatic variation— remains valid.

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5.1 Glacial Dynamics

Glaciers are masses of granular snow and ice formed by compaction and recrystallization of snowfall, lying largely or wholly on land and showing evidence of past or present movement. The transformation of snow into ice in thicknesses great enough to promote motion on land is important. In addition to low temperatures, precipitation is needed for glaciers to develop. Some polar areas have no glaciers because even though the climate is cold, little snowfall occurs and the conditions needed to convert snow into ice occur infrequently.

Because the formation and persistence of glaciers are directly linked to climate, their deposits and landforms provide evidence for interpretation of past climatic changes. Thus an understanding of glacial processes is important for the study of ancient climates.

Although ice is solid at atmospheric pressure, it has low shear strength and will readily deform plastically under shear stresses beyond 1 kg/cm^2, resulting in continuous plastic flow.

ε (strain) = k[ρ(ice density) g (gravity) t (ice thickness) sin α (slope of ice surface)]^n

The constant (k) increases with temperature, as does the n^{th} power in this equation. Thus, plastic flow in ice is very sensitive to temperature—the warmer the ice, the more easily it deforms. Strain rates at 0°C may be 10 times greater than at -22°C. Temperate glaciers, which are near the pressure-melting point of ice, generally exhibit higher rates of plastic flow than do polar glaciers, whose temperature is well below the freezing point. As seen in the equation above, not only temperature but also ice thickness and the slope of the ice surface affect flow velocity. The thicker the ice, the faster it flows, and the steeper the ice surface, the faster it flows.

In addition to plastic flow, glaciers also move by sliding over their bed. Basal sliding of glaciers increases where subglacial meltwater is present, especially if the subglacial water is under hydrostatic pressure, which then reduces the effective weight of the overlying ice and diminishes friction. Basal sliding is thus greatest in temperate glaciers and may be absent in polar glaciers, which are frozen to their base.

In general glaciers grow, flow, and melt continuously, within the context of an overall annual mass budget of gains and losses that is not necessarily balanced over time. Snow falls on high ground, compacts, and becomes solid ice. More precipitation of snow forms another layer on the top, so the ice grows thicker by the addition of new layers at the surface. When the ice is thick enough it starts to flow plastically under the force of gravity.

The mechanism of glacier flow needs to be considered carefully. Ice does not simply slide on its base. Nonetheless, sliding is a significant contributor of downslope movement for some glaciers, varying between 0 percent for the Meserve Glacier (Antarctica) and 75 percent for the Athabaska Glacier (Canada) (Paterson, 1981; Holdsworth and Bull, 1970).

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5.1.1 Plastic Flow

When stress in ice exceeds its elastic limit, ice becomes plastic; this allows limitless permanent deformation to occur, because the ice flows continuously under its own weight. Ice flows plastically by three mechanisms, namely:

- intergranular shifting,
- intragranular shifting, and
- recrystallization.

In intergranular shifting, differential movement takes place between ice grains by rotation and sliding between individual ice crystals. For intragranular shifting, movement occurs by gliding along basal planes within ice crystals; this is a significant mechanism of glacial flow, easy slippage occurring along planes parallel to the base of the crystals, where fewer atomic bonds need to be broken for translation to occur. Recrystallization of ice facilitates down-glacier transfer of material by creep. Pressure at grain boundaries can melt ice at the pressure melting temperature, and meltwater can then migrate to sites of lower pressure (in the down ice direction), where it refreezes. The net effect of these three processes is plastic flow of the ice.

Three factors determine the magnitude of plastic flow in ice, namely:

- creep is proportional to temperature;
- creep is proportional to ice thickness (i.e., to the stress produced by the weight of overlying ice); and
- creep is proportional to the slope of the ice surface.

The closer the temperature comes to the melting point, the greater is the creep rate. The creep rate at -1^o C is about 1,000 times greater than at -20^o C.

The stress law of creep means the thicker the ice, the faster the flow. In valley glaciers the upper 30 m of the glacier cannot flow, because the ice is brittle and cracks to form crevasses in the rigid ice that is carried along on the plastically flowing lower ice. Because they are near melting point, valley glaciers do not have to be very thick to flow—a little over

30 m may be sufficient. The depth of the crevasses marks the threshold between brittle and plastic ice—at which level the yield stress[1] is reached. By contrast, a great stress is required to cause flow if the temperatures are very low as in polar glaciers.

Though the direction of movement of the terminus of a glacier is the simplest indicator of where the balance of accretion and ablation lies, this in itself tells us nothing about the *cause* of any change.

Himalayan glaciers present a distinctive variation of the typical flow mode. Whereas many glaciers start from icecaps that flow to the terminus, with continuous flow from the snow-collecting area to the glacier snout, many of those in the Himalayas are avalanche-fed. Relief is so great, and the peaks are so sharp, that snow falling on the peaks reaches the glaciers in the valleys via avalanches. The growth of such glaciers depends not just on precipitation, then, but on the frequency of avalanches. It could happen, for example, that increased temperature in the mountains caused increased avalanching, thereby thickening the glaciers and causing increased flow.

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[1] The *yield stress* in ice is the stress above which behavior changes from that of a solid with brittle (elastic) properties to a material with ductile flow.

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5.2 Glaciers as Paleo-thermometers

Temperature not only affects flow rates in glaciers but also plays a critical role in the accumulation and ablation of snow and ice that control whether glacier termini advance or retreat.

The annual difference in mass between accumulation and ablation on a glacier is the net mass balance. Accumulation dominates in the winter, ablation in the summer. If the two are equal, then the net balance of the glacier is zero; if accumulation is greater, the net balance will be positive; and if ablation is greater, the net balance will be negative.

A glacier having a protracted negative net mass balance loses ice not only by retreat of the terminus but also by substantial thinning or downwasting of the glacier. Because rates of glacial movement are a function of ice thickness, thinning of the ice reduces the rate of ice transfer down glacier, and the rate of retreat and downwasting increases. Thus, acceleration of terminal retreat in a glacier does not necessarily indicate accelerated climatic warming. Nonetheless, because climatic factors control accumulation and ablation rates, glaciers are often used as indicators of past climatic conditions. Figure 5.2.1 illustrates the relationship between climate and glacial response.

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5.3 Modern Global Ice Volume and Mass Balance

Ice is naturally present on Earth's surface in three main geomorphic forms: land-based icecaps (Greenland and Antarctica), mountain-valley glaciers, and floating sea ice. Today, nearly 30 million km^3 (91 percent) of all land ice is in Antarctica, 2.6 million km^3 (8 percent) is in Greenland; all other valley glaciers added together have a volume a little less than 0.2 million km^3 (0.6 percent) (Poore *et al.*, 2011). Any consideration of the global ice budget, and changes within it, must start by acknowledging these bounding parameters of ice distribution.

Of the approximately 160,000 glaciers currently known to exist, only 67,000 (42 percent) have been inventoried to any degree (Kieffer *et al.*, 2000). Mass balance data (net positive for glacier growth, negative for shrinkage) exist for more than a single year for only just over 200 glaciers (Braithwaite and Zhang, 2000). When the length of record increases to five years, this number drops to 115; if both winter and summer mass balances are required, the number drops again to 79. Only 42 glaciers have records longer than 10 years. "That many glacierized regions of the world remain unsampled, or only poorly sampled" (Braithwaite and Zhange, 2000) represents a major problem for those wishing to undertake accurate global mass balance research.

Clearly, we know very little about the true state of most of the world's glaciers. Moreover, and despite media alarmism about the issue, mountain glaciers worldwide contain just 45 cm of sea-level change equivalent, and their melting is therefore largely irrelevant to concerns about sea-level rise. Major sea-level change from melting ice depends practically on the relative ice balance of the large Antarctic (73 m sea-level equivalent) and Greenland (7 m sea-level equivalent) icecaps (Poore *et al.*, 2011).

It is useful to distinguish two main lines of evidence as to whether modern changes in the mass balance of the cryosphere are unusual. The first of these is a comparison of modern with historic and

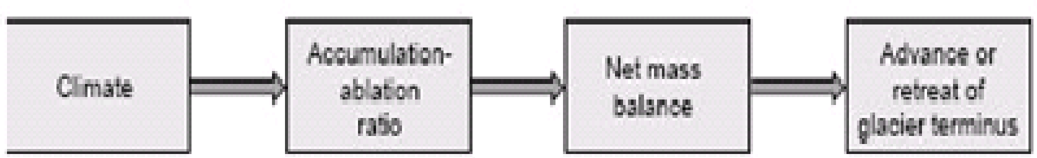

Figure 5.2.1. Relationship between and among climate, accumulation/ablation, net mass balance, and position of a glacier terminus. Adapted from Easterbrook, D.J. 1993. *Glacial Processes; Surface Processes and Landforms*. Prentice Hall, pp. 293–332.

Holocene changes in mountain glaciers, back to 11,700 years BP. It is, for example, well established that major glacial advances occurred between the fifteenth and nineteenth centuries, during a period of colder global temperature known as the Little Ice Age (Broecker, 2001; Grove, 2001). Many records indicate widespread glacial retreat thereafter, as temperatures began to rise in the mid- to late-1800s, and many glaciers have since shrunk in size and returned to a position characteristic of their pre-Little Ice Age state.

Second is the question of whether modern glaciers and icecaps are in a uniform, or indeed accelerating, state of retreat, as many commentators have alleged. The detailed evidence regarding this is presented below under the appropriate headings. To date, however, no research has contradicted the findings of Dowdeswell *et al.* (1997) and Braithwaite (2002).

In an analysis of Arctic glacier mass balance, Dowdeswell *et al.* (1997) found that of the 18 glaciers with the longest mass balance histories, more than 80 percent displayed negative mass balances over their periods of record. In addition, "almost 80% of the mass balance time series also have a positive trend, toward a less negative mass balance." Because of the multiple warm and cool periods of the past century—two periods of cooling (1880–1915 and 1945–1977) and two periods of warming (1915–1945 and 1978–1998)—glaciers have both advanced and retreated. No global warming has occurred since 1998 and glaciers appear to be in a transition period.

Braithwaite (2002) reviewed mass balance measurements of 246 glaciers made between 1946 and 1995, spanning both the 1946–1977 cool period and the 1978–1998 warm period. He found "several regions with highly negative mass balances in agreement with a public perception of 'the glaciers are melting,' but there are also regions with positive balances." Within Europe, for example, he notes "Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980–95." When results for the whole world are combined for this most recent period of time, Braithwaite notes "there is no obvious common or global trend of increasing glacier melt in recent years."

The glacier with the longest mass balance record is the Storglaciaren glacier in northern Sweden. The first 15 years of its 50-year record showed a negative mass balance with little trend. Thereafter, however, its mass balance became positive during the latter part of the 1945–1977 cool period (Braithwaite and Zhang, 2000).

Although glaciers have advanced and retreated during alternating warm and cool periods, since the Little Ice Age (LIA) glaciers have lost mass as Earth thawed. No "unprecedented warming" occurred in the latter part of the twentieth century. Rather, glaciers retreated strongly during the 1915–1945 warm period before major industrial CO_2 emission and advanced during the 1945–1977 cool period when CO_2 emissions were soaring—just the opposite of what should have happened if CO_2 caused global warming and glacial melting.

Conclusion

No substantive evidence exists that the rate of glacier retreat has increased over the past 70 years, a time of large increases in CO_2 emissions. The common claim that most glaciers are today retreating or melting in response to human carbon dioxide emissions is incorrect. The global data on glacial mass balance simply do not support the claims made by the IPCC that most glaciers are today retreating or melting.

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5.4 Antarctic Ice Cap

Antarctica covers 14.0 million km^2 (5.4 million sq mi) and is Earth's fifth-largest continent (see Figure 5.4.1). Glacial ice covers about 98 percent of Antarctica. It is the coldest, driest, and windiest continent and has the highest average elevation of all the continents. Antarctica has about 91 percent of the world's ice, representing about 70 percent of the world's fresh water.

Antarctica is also by far the coldest continent, with the coldest temperature ever recorded being --89.2 °C at the Russian Vostok Station on July 21, 1983. Temperatures in the interior are often -80°C with low precipitation, making Antarctica a frozen desert. The South Pole averages less than 10 cm of snow per year.

East Antarctica, the highest part of the continent, is covered by the East Antarctic Ice Sheet, which reaches thicknesses of 4,776 m with a mean thickness of 2,225 m. At its lowest point Antarctica is 2,480 m below sea level.

West Antarctica makes up a much smaller area and is covered by the West Antarctic Ice Sheet. The West Antarctic Peninsula extends northwest from the main continent (see Figure 5.4.1) and contains only a small proportion of the total ice in Antarctica.

The study of Antarctica's climate has provided valuable insights and spurred contentious debate over issues of global climate change. Climate model results project warming for polar regions under enhanced greenhouse gas emissions, leading many to anticipate Earth's polar regions will experience severe responses to rising CO_2 levels. Real-world data from Antarctica do not support such expectations. In the 2009 and 2011 NIPCC reports, scientific analyses are described that demonstrate nothing unusual, unprecedented, or unnatural about the present climate of the large Antarctic ice sheet.

Among the commonest lines of evidence cited for unusual melting of Antarctic ice is the breaking away of large pieces of glacier termini or ice shelf. Warm ocean water around the West Antarctic Peninsula regularly causes some melting of ice and breaking off of pieces of shelf ice, but the volumes affected are only a small percentage of the main Antarctic ice sheet. The glaciological processes involved are entirely normal and natural; no evidence has been found to show the process of glacial calving around Antarctica is any different today than in the past.

For example, in November 2001 a large iceberg separated from West Antarctica's Pine Island Glacier. This event created great interest because the Pine Island Glacier is the fastest-moving glacier in Antarctica and discharges the largest volume of ice. Some speculated this event might herald the

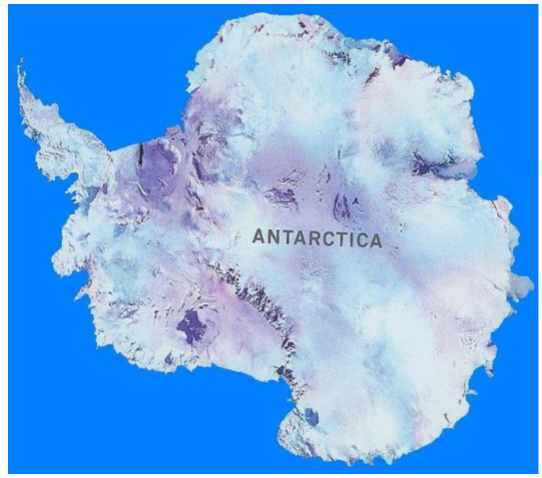

Figure 5.4.1. UPPER. Satellite view of the Antarctic Ice Sheet. LOWER. Digital terrain map of the subglacial rock topography of Antarctica, colorized as to height, after removal of the ice and correction for isostatic rebound and sea level change (NASA images).

"beginning of the end" of the West Antarctic Ice Sheet. Scientific studies suggest otherwise.

Rignot (1998) employed satellite radar measurements of the grounding line of Pine Island Glacier from 1992 to 1996 to determine whether it was advancing or retreating. The data indicated a retreat rate of 1.2 ± 0.3 kilometers per year over four years. Subsequently, Stenoien and Bentley (2000) used radar altimetry and synthetic aperture radar interferometry to prepare a velocity map of the ice catchment region, which revealed a system of tributory ice-flow streams that feed the main, fast-flowing trunk glacier. By combining velocity data with ice thickness and snow accumulation rates, they calculated an approximate mass balance for the glacier with an uncertainty of ~30%. Their results suggested the mass balance of the catchment region was not significantly different from zero during recent years.

Hall (2009) concludes for many localities around Antarctica "ice extent was less than at present in mid-Holocene time," suggesting "the magnitude of present ice recession and iceshelf collapse is not unprecedented."

Evidence for previous ice shrinkage during warmer parts of the Holocene in the western Ross Sea region has been provided by Hall and Denton (1999, 2002) based on the distribution and dating of surficial and terrace deposits. Their research shows "the Wilson Piedmont Glacier was still less extensive than it is now" during the Medieval Warm Period. Together with Baroni and Orombelli (1994a), they also provided evidence for "an advance of at least one kilometer of the Hell's Gate Ice Shelf within the past few hundred years."

Hall and Denton conclude the Ross Sea area evidence suggests "late-Holocene climatic deterioration and glacial advance (within the past few hundred years) and twentieth century retreat." Comparison with dated moraines elsewhere in the world shows the reported Wilson Glacier advance overlaps with similar Little Ice Age advances known from the South Sheltland Islands (Birkenmajer, 1981; Clapperton and Sugden, 1988; Martinez de Pison *et al.*, 1996; Björck *et al.*, 1996), New Zealand (Wardle, 1973; Black, 2001), and even Europe.

Further support for a Holocene history puncutated by ice advance and retreat is provided by Hall's (2009) comprehensive circum-Antarctic review, which found "glaciers on most if not all" of the Indian/Pacific-sector sub-Antarctic Islands "underwent advance in the last millennium, broadly synchronous with the Little Ice Age," and "glaciers in all areas" have "subsequently undergone recession," but only in "the past 50 years."

Tedesco and Monaghan (2010) studied records collected since the launch of passive microwave radiometers in 1979, finding for the past three decades the continent-wide snow and ice melting trend has been "negligible." They also report between 1979 and 2009 snow and ice melt was at a "record" low, marking a "new historical minimum"; "December 2008 temperature anomalies were cooler than normal around most of the Antarctic margin"; and the "overall sea ice extent for the same month was more extensive than usual."

Vaughan *et al.* (2003) note "historical observations since 1958 at Esperanza Station document warming equivalent to 3.5 ± 0.8°C per century," marking the Antarctic Peninsula as among the most rapidly warming regions on Earth. To establish whether this warming is unusual in any way, Mulvaney *et al.* (2012) analyzed deuterium/hydrogen isotope ratios (δD) of an ice core from James Ross Island at the northeastern tip of the Antarctic Peninsula to develop a late glacial and Holocene temperature history for the region. They found the Antarctic Peninsula experienced a Holocene warm period 9,200–2,500 years ago, similar to modern-day levels. They also found "the high rate of warming over the past century is unusual (but not unprecedented) in the context of natural climate variability over the past two millennia." More specifically, the temperature of James Ross Island has increased by 1.56 ± 0.42°C over the past 100 years, and at a rate of 2.6 ± 1.2°C over the past half-century. Mulvaney *et al.* conclude this is "highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era."

Conclusions

These studies establish that on the shorter, meteorological time scale the Antarctic ice mass is effectively stable.

On the longer-term climatic scale, glacial activity on and around Antarctica has fluctuated in parallel with the millennial-scale ice volume variability evident throughout the world, including recession during the Medieval Warm Period to positions that have not been attained again today, followed by significant advances during the intervening Little Ice Age and recession again during the nineteenth and twentieth century natural warming episode.

Moreover, the modern warming of the Antarctic Peninsula falls within the bounds of natural variation during the Holocene.

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5.5 Greenland Ice Cap

Only a small part of global ice volume is represented today by the Greenland Ice Cap (8 percent of the total), and during the last great glaciation, 20,000 years ago, the Greenland massif comprised an even smaller part of a much larger circum-Arctic Eurasian-American icecap, most of which has now melted.

Despite its small size, an understanding of the controls on formation and melting of the Greenland Ice Cap remains important. Interest in Greenland and other Arctic ice-covered areas is also much enhanced by the nearby presence of Scandinavian and North American countries, whose citizens are alert to the conservation of their Arctic environment and its biota, including iconic species such as the polar bear.

The topographic map of the Greenland Ice Cap shows a broad dome, leading to the common assumption that the icecap is underlain by a dome-shaped continent. A map of the base of the ice shows this is not true. Instead a kilometer-deep basin extends below sea level under the Greenland interior, the sub-ice terrain being a bowl formed by a ring of mountains with few openings to the sea. This results from the mass of the icecap being heavy enough to cause isostatic sinking of the land.

Importantly, therefore, the ice cannot simply slide into the sea as is often alleged. Instead, ice near the base of the icecap flows upwards to join glaciers flowing through gaps in the mountain rim. According to the IPCC's *Fourth Assessment Report*, melting of the whole ice sheet would contribute nearly 7 m to sea-level rise (Bergmann *et al.* 2012). Yet if the whole ice sheet could suddenly melt, much of the water would be retained in a huge lake bounded by the mountain rim. In any case, the distribution of annual mean temperatures on Greenland is such that melting is possible only around the periphery (Figure 5.5.1).

In 2006, several commentaries and articles in a celebrated issue of *Science* magazine described accelerating discharges of glacial ice from Greenland and gave dire warnings of an imminent large, rapid, and accelerating sea-level rise as one result (Bindschadler, 2006; Ekstrom *et al.*, 2006; Joughin, 2006; Kerr, 2006; Kennedy and Hanson, 2006; Otto-Bliesner *et al.*, 2006; Overpeck *et al.*, 2006). The center of the discussion was Ekstrom *et al.*'s identification of a 2002–2005 increase in micro-earthquakes beneath outflowing glaciers on the east and west coasts of Greenland, between approximately 65°N and 76°N latitude, which they argued indicated enhanced and potentially dangerous glacial flow.

The implied conclusion from the *Science* papers—that the changes were the result of human-caused global warming—was not shared by Joughlin (2006), who showed summer temperatures at locations within the glacial earthquake area were warmer during the 1930s than in 2002–2005. Joughlin concluded the period of recent warming in Greenland "is too short to determine whether it is an anthropogenic effect or natural variability."

Przybylak (2000) published a comprehensive meteorological analysis that provides strong support for Joughin's conclusion, stating, "the level of temperature in Greenland in the last 10–20 years is similar to that observed in the 19th century" and citing corroborating evidence for an earlier warm Arctic in the 1930s and 1950s. Przybylak's concluded the meteorological record "shows that the observed variations in air temperature in the real Arctic are in many aspects not consistent with the projected climatic changes computed by climatic models for the enhanced greenhouse effect," because "the temperature predictions produced by numerical climate models significantly differ from those actually observed." These conclusions are supported by Greenland temperature records dating back to 1880 (Figure 5.5.2).

The studies discussed so far fail to take adequate account of the Holocene context within which modern glacial change must be considered. The record indicates warmer temperatures were the norm in Greenland in the earlier part of the past 4,000 years, including century-long intervals nearly 1° C warmer than the recent decade of 2001–2010 (Chylek *et al.*, 2004, 2006; Easterbrook, 2011). The current decadal mean temperature in Greenland has not exceeded the envelope of natural variability over the past 4,000 years.

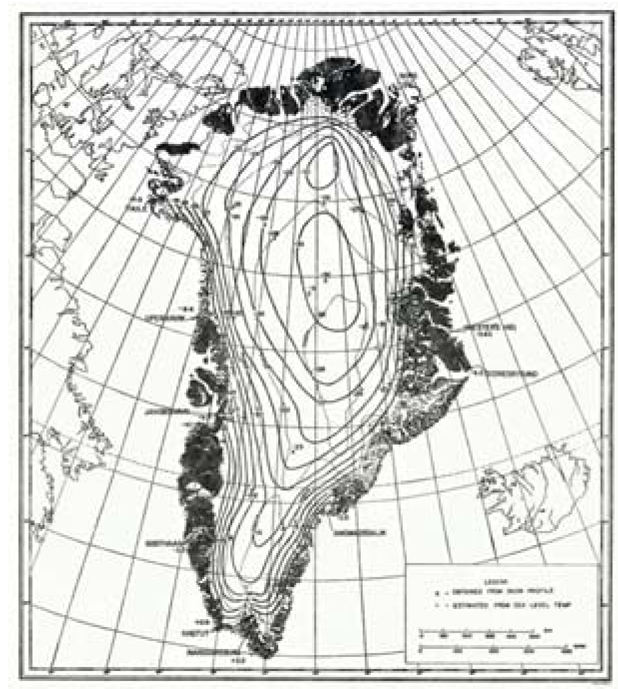

Figure 5.5.1. Mean annual temperature on the Greenland Ice Cap. Ice melting can only occur where the temperature exceeds the melting point. These conditions only occur at the edges of the icecap, where continued melting depends on glacially-slow flow to replace the melted ice. Adapted from Box, J.E., Yang, L., and Bromwich, D.H. 2009. Greenland Ice Sheet surface air temperature variability: 1840–2007. *Journal of Climate* **22**: 4029–4049.

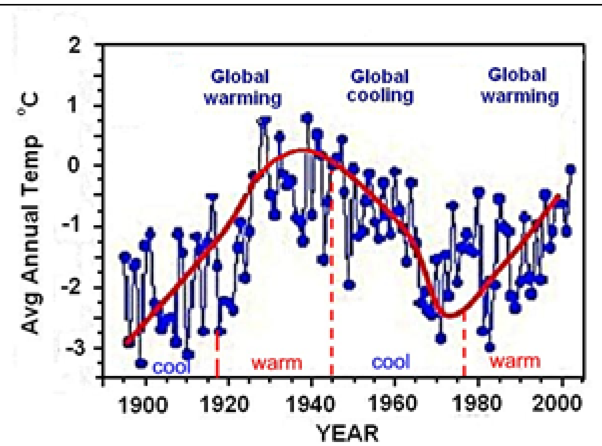

Figure 5.5.2. Temperatures in Angmagssalk, Greenland, since 1890, showing a multidecadal pattern of warmings and coolings. Note temperatures in the 1930s were higher than modern temperatures. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221.

Kobashi *et al.* (2011) reconstructed high-resolution (~10 yr) records of the past 1,000 and past 160 years of Greenland's snow surface temperature, which also delineate clear multidecadal to multicentennial temperature fluctuations (see Figure 5.5.3). In keeping with more generalized climatic histories, these records are characterized by a warm period in the eleventh and twelfth centuries (the Medieval Warm Period), a long-term cooling toward the coldest period in the seventeenth and eighteenth centuries (the Little Ice Age), and the observed most recent warming (1978–2000).

Greenland underwent a 33 percent greater warming in 1919–1932 than the warming in 1994–2007 (Box *et al.*, 2009), and the recent decadal average temperature is similar to that of the 1930s–1940s (Chylek *et al.*, 2006; Box *et al.*, 2009). Kobashi *et al.* (2011) note the 2000–2010 decadal average surface temperature at the Greenland ice sheet summit, the warm period of the 1930s–1940s, and the Medieval Warm Period indicate "the present decade is not outside the envelope of variability of the last 1000 years."

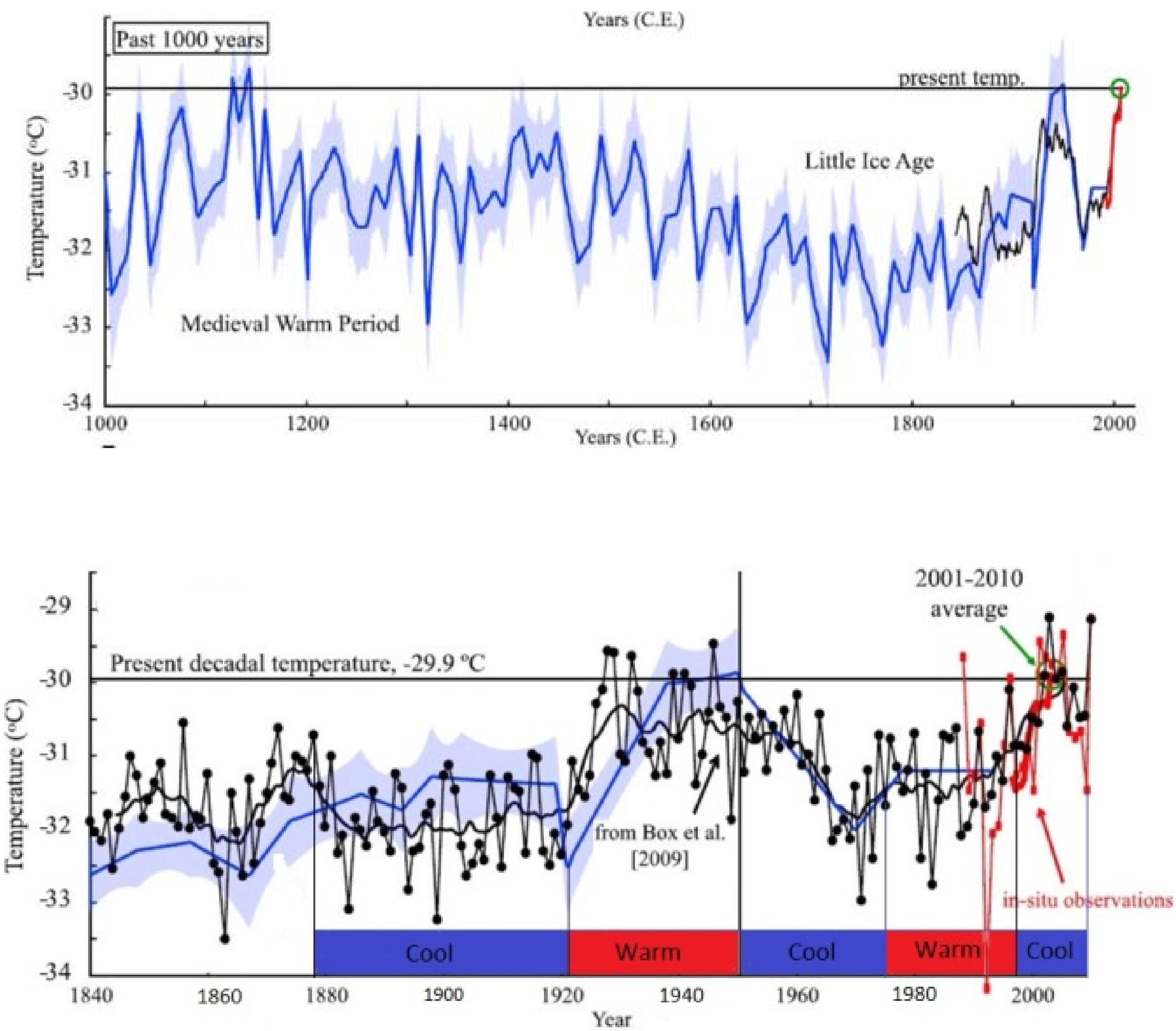

Figure 5.5.3. Reconstructed Greenland snow surface temperatures for the past 4000, 1,000 and 160 years. The alternating warm and cool periods correlate well with measured temperatures and other reconstructions. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

Conclusion

The temperatures of 2000–2010 in Greenland have been exceeded on more than 70 occasions in the past 4,000 years. Recent warmth is not unprecedented, and none of it was necessarily caused by rising CO_2.

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Other research

A number of recent publications on the ice history of Greenland and nearby islands have demonstrated significant ice loss occurred in the twentieth century, in some part during periods of strong warming.

- Mernild *et al.* (2008) describe the 1993–2005 glacial history of Mittivakkat Glacier, on Ammassalik Island, Greenland, as having an overall "mass balance (that) has been almost continuously negative, corresponding to an average loss of glacier volume of 0.4% per year." This and earlier ice loss occurred against the background of instrumental warmings recorded for 1918–1935 at 0.12°C per year and for 1978–2004 at 0.07°C per year." These authors also report "the warmest average 10-year period within the last 106 years was the period from 1936–1946 (-1.8°C)," while the second warmest period was from 1995–2004 (-2.0°C). In addition, they note the period 1936–1946 was the warmest period within the last 106 years in West Greenland (Cappelen, 2004).
- Frauenfeld *et al.* (2011) also report Greenland ice melt has been increasing during the past three decades, with the melt extent observed in 2007 being the greatest on record as observed from satellite records. They comment the "total annual observed melt extent across the Greenland ice sheet has been shown to be strongly related to summer temperature measurements from stations located along Greenland's coast, as well as to variations in atmospheric circulation across the North Atlantic."

To test whether these changes might represent unprecedented modern (and anthropogenic) warming, Frauenfeld *et al.* reconstructed a record of annual ice melt extent across Greenland that extends back for 226 years, combining more recent satellite-derived observations with older melt extent values based upon historical observations of summer temperatures and winter circulation patterns. They conclude "the recent period of high-melt extent is similar in magnitude but, thus far, shorter in duration than a period of high melt lasting from the early 1920s through the early 1960s." Although the greatest recorded melt extent did indeed occur in 2007, the occurrence was not statistically significantly different from 20 older melt seasons, most during 1923–1961.

Frauenfeld *et al.* note “there is no indication that the increased contribution from the Greenland melt in the early to mid-20th century ... resulted in a rate of total global sea level rise that exceeded ~3 mm/yr.” Instead, their results indicate “Greenland’s contribution to global sea level rise, even during multi-decadal conditions as warm as the past several years, is relatively modest.”

- A common worry regarding ice wastage is that in summer surficial meltwater will penetrate through crevasses to lubricate faster flow at the base of the glacier (Iken and Bindschadler, 1986; Mair *et al.*, 2002; Truffer *et al.*, 2005; Bamber *et al.*, 2007; Bartholomaus *et al.*, 2008; van de Wal *et al.*, 2008; Shepherd *et al.*, 2009; Schoof, 2010; Sundal *et al.*, 2011). Given that much glacier flow occurs by intracrystalline plastic processes, this worry is based on the speculative assumption of additional flow by sliding along the glacier-bedrock contact. Hoffman *et al.* (2011) have reported “basal lubrication by surface meltwater penetrating the Greenland Ice Sheet generates summer speedups of 50-200% for the regions of the ablation zone experiencing sheet flow.”

To investigate this phenomenon further, Hoffman *et al.* compared temperature measurements made at two weather stations; episodic supraglacial lake drainage events observed on Landsat images made at fortnightly intervals between early June and late August 2007; and ice velocity as recorded at nine GPS stations located across a 50 km swath of the western Greenland Ice Sheet. Calculation of strain rates and bed separation demonstrated the occurrence of “an early summer background period of constant ice velocity in west Greenland, followed by a speedup that lasted most of the summer and was associated with surface melt.” They also found “areas in the ablation zone typically experienced [only] one to two velocity events that are inferred to result from supraglacial lake drainage” and “in all cases the effects are short-lived (less than one day) and local (less than 10 km).” It is therefore unlikely rising temperatures are able to generate a positive feedback that causes significant glacial mass loss. Though Hoffman *et al.* say “episodic pulses of water are key for generating enhanced sliding,” they add “these daily increases in velocity are superimposed on a night time velocity that generally decreases over the season … support(ing) the idea that rising air temperatures in Greenland may not translate directly into increased sliding at the seasonal scale.” Similar results have been reported by earlier writers, including Zwally *et al.* (2002), Joughin *et al.* (2008), van de Wal *et al.* (2008), Shepherd *et al.* (2009), Bartholomew *et al.* (2010), Sundal *et al.* (2011), and Palmer *et al.* (2011).

Conclusions

It has been claimed that CO_2-induced global warming should be expressed most strongly in the Arctic, and its effects therefore should be evident there before anywhere else, making the Arctic the “canary in the coal mine” for those concerned about dangerous global warming. Though some localities in Greenland did indeed record significant ice retreat during the twentieth century, at other places, such as the Flade Isblink Ice Cap, ice accreted in sufficient amounts to cancel out the ice loss elsewhere.

The studies reported above make clear that any recent upswing in glacial outflow activity on Greenland has no necessary or likely relationship with anthropogenic global warming, as late twentieth century temperatures did not rise either as fast or as high as they did during the great natural warming of the 1920s–1930s.

The spectacular, and therefore often filmed, coastal glacial collapses or surficial meltwater streams plunging into crevasses represent only half of the equation relating to ice-sheet “collapse” and threatened sea-level change, the other half being the rate of inland ice accumulation derived from snow precipitation. Recent satellite radar altimetry suggests Greenland is in a state of approximate mass balance, quite contrary to the alarmist tone of the 2006 *Science* studies.

The argument that the modern Greenland Ice Cap is melting under the influence of anthropogenic warming is also greatly weakened by new stratigraphic evidence for Eocene-Oligocene ice in the Northern Hemisphere (Eldrett *et al.*, 2007), which is “about 20 million years earlier than previously documented, at a time when global deep water temperatures and, by extension, surface water temperatures at high latitude, were much warmer.” We now have evidence of a much warmer period of time during which the Greenland Ice Sheet failed to melt. In addition, “palaeoclimate model experiments generate substantial ice sheets in the Northern Hemisphere for the Eocene only in runs where carbon dioxide levels are lower (approaching the pre-anthropogenic level) than suggested by proxy records.”

The Little Ice Age lasted in Greenland until 1918, longer than it did in many other places, which doubtless helped to achieve a post-LIA rate of warming between 1918 and 1935 some 70 percent greater than the warming from 1978 to 2004—even though the mean rate-of-rise of the atmosphere's CO_2 concentration in the late twentieth century was nearly five times greater than during the 1920s–1930s warming. Greenland expereienced more rapid warming in the earlier period of slow CO_2 rise, and slower warming in the latter period of rapid CO_2 rise.

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5.6 Other Arctic Glaciers

A perception existed until recently that high Arctic glaciers, especially those in Iceland and Svalbard (Spitzbergen), have been uniformly undergoing a reduction in ice volume since the mid-1990s.

Rinne *et al.* (2011) used satellite-borne radar altimetry to map elevation changes of the Flade Isblink Ice Cap (FIIC), northeast of Greenland, between 2002 and 2009. FIIC is the largest icecap in Greenland separate from the Greenland Ice Sheet, covering an area of 8,500 km^2. The measurements showed elevation gain (ice accretion) of up to 2 m/yr over most of the icecap, and elevation loss of up to 1 m/yr (ice melting) in lower, peripheral areas. The authors also reported a thickening, and inferred slowing of flow, of three outlet glaciers northeast of Station Nord. This confirmed the findings of Joughin *et al.* (2010), who, based on satellite-measured velocities, reported a slowdown from 300 m/year to 60 m/year for two of these glaciers between 2000 and 2006. Overall, Rinne *et al.* found "the net mass change rate of the FIIC to have been zero (0.0 ± 0.5 Gt/year) during 2002–2009."

Rolsted Denby and Hulth (2011) used geodetic data derived from optical imaging back to 1949 to determine whether such reductions also applied to Jan Mayen Island, a 373-km^2 glaciated volcanic island located in the North Atlantic Ocean between Iceland and Svalbard at latitude 71° N. They found over the 33-year period 1975–2008 the ice volume in the southern part of Jan Mayen Island increased; there was also an increase in ice volume over the 59-year period 1949–2008, although the result was not statistically significant. These increases occurred despite a parallel increase in the annual mean temperature of the region by 1.58°C over the past 30 years, which drove a peripheral sea-ice retreat.

This combination of circumstances suggests where warming prevents winter sea-ice formation, the extra moisture made available by evaporation can enhance precipitation (in the form of snowfall) on coastal glaciers, and hence their growth even in a warming environment.

Moholdt *et al.* (2012) used data from the Ice, Cloud, and Land Elevation Satellite (ICESat) and the GRACE gravity satellites to assess the glacier mass budget between October 2003 and October 2009 for a total glaciated area of 51,500 km^2 in the Russian High Arctic (Franz Josef Land, Severnaya Zemlya, and Novaya Zemlya). Their results were placed in a slightly longer-term climatic context by consideration of meteorological data from 1980 to 2009. As shown in Figure 5.6.1, significant glacial mass loss has occurred on Novaya Zemlya, less in Severnaya Zemlya, and a marginal increase in Franz Josef Land. All three records show a tendency for an increase in ice mass over the last two years. Of course, no hard conclusions can be reached on the basis of such a short and variable record; moreover, much uncertainty is attached to studies that utilize GRACE data because of the uncertainty of current geoid models (Houston and Dean, 2012).

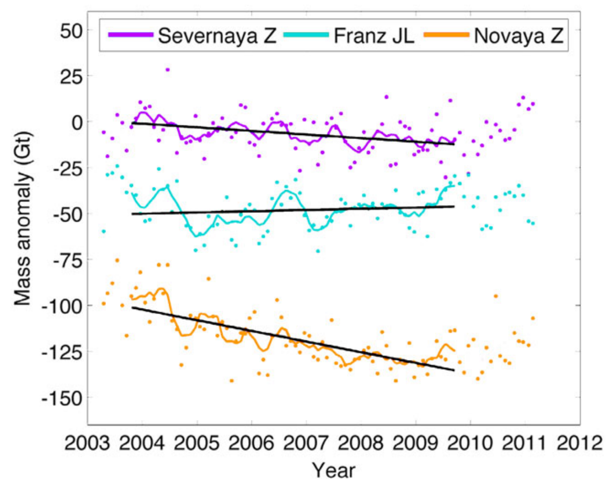

Figure 5.6.1. Monthly glacier mass anomalies (dots) as determined from GRACE, where colored curves are five-month running means of monthly data and black lines are linear fits to the monthly data within the ICESat for October 2003–October 2009. Adapted from Moholdt, G., Wouters, B., and Gardner, A.S. 2012. Recent mass changes of glaciers in the Russian High Arctic. *Geophysical Research Letters* **39**: 10.1029/ 2012GL051466.

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Earlier research

Here we provide brief summaries of earlier published and NIPCC-summarized evidence for historic trends in Arctic glacier behavior, to see if it corresponds to the pattern of melting and retreat predicted by IPCC modeling.

- Dowdeswell *et al.* (1997) analyzed the mass balance records of the 18 Arctic glaciers with the longest observational histories, 80 percent of which displayed negative mass balances over their period of measurement. Ice core records from the Canadian High Arctic islands support this finding, and the researchers concluded the "generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age."
- Calkin *et al.* (2001) provide a comprehensive review of Holocene glaciation along the northernmost Gulf of Alaska, between the Kenai Peninsula and Yakutat Bay. Several periods of glacial advance and retreat are identified over the past 7,000 years. A general ice retreat during the Medieval Warm Period lasted for "at least a few centuries prior to A.D. 1200," after which the three major intervals of Little Ice Age—in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century—were accompanied by glacial expansion and depression of ice equilibrium-line altitudes by 150–200 m below present values.
- Zeeberg and Forman (2001) analyzed twentieth century changes in glaciers on north Novaya Zemlya—a Russian island located between the Barents and Kara Seas in the Arctic Ocean. Here, an accelerated post-Little Ice Age glacial retreat occurred in the first and second decades of the twentieth century. By 1952 the region's glaciers had experienced 75 to 100% of their net twentieth century retreat, and during the next 50 years the recession of more than half of the glaciers stopped, while many tidewater glaciers began to advance. Instrumental records show the most recent of these glacial stabilizations and advances occurred in response to increases in precipitation and/or decreases in temperature.
- Mackintosh *et al.* (2002) described the 300-year history of the Solheimajokull outlet glacier on the southern coast of Iceland. In 1705, this glacier had a length of about 14.8 km; by 1740 it had grown to 15.2 km in length, after which it retreated to a minimum length of 13.2 km in 1783. Rebounding rapidly, the glacier returned to its 1705 extent by 1794 and its 1740 length by 1820. This maximum length was maintained for the next half-century, after which the glacier contracted slowly to lengths of 14.75 km in 1932 and 13.8 km in 1970, after which rapid expansion occurred to 14.3 km by 1995. Currently, the glacier terminus falls about midway between its maximum and minimum positions of the past three centuries, and Mackintosh *et al.* report "the recent advance (1970–1995) resulted from a combination of cooling and enhancement of precipitation."
- Humlum *et al.* (2005) evaluated the climate dynamics of high-latitude glaciers in the Svalbard Archipelago, especially the Longyearbreen glacier in arid central Spitzbergen (latitude 78°13'N). They found the Longyearbreen glacier "has increased in length from about 3 km to its present size of about 5 km during the last c. 1100 years," and they suggest this late-Holocene glacial growth is probably widespread in Svalbard and adjoining Arctic regions. Climate in Svalbard changed sharply more than once in the twentieth century, with Arctic-record rates of temperature rise in the early 1920s, followed by a nearly equivalent temperature drop four decades later. The Longyearbreen glacier changed in concert, and the current position of its terminus suggests this region of the Arctic is currently experiencing some of the lowest temperatures of the entire Holocene at a time of high atmospheric CO_2 concentration.
- In a late Holocene study, Bradwell *et al.* (2006) examined the link between fluctuations of Lambatungnajokull glacier, southeast Iceland, and variations in climate. Comparison between the glacial history and instrumental records show over the past four centuries "there is a particularly close correspondence between summer air temperature and the rate of ice-front recession of Lambatungnajokull during periods of overall retreat"; recession was greatest during the 1930s and 1940s, when it averaged 20 m/year, but thereafter it slowed so "there has been little overall retreat since the 1980s." The twentieth century part of this glacial history is shared by other nearby glaciers, consistent with the full 400-year history being typical for the wider region.

Conclusions

Computer simulations of global climate change indicate polar regions should show the first and most severe signs of CO_2-induced global warming. These signs were expected to become especially evident in the second half of the twentieth century, when approximately two-thirds of the rise in industrial CO_2 emissions occurred and Earth's temperature allegedly rose to unprecedented levels.

The evidence is clear regarding these postulates: The many papers summarized above do not find high Arctic glaciers are uniformly wasting away. Instead, as some glaciers advance, others retreat, with the Jan Mayen example showing as well that some advances are actually accompanied by warming rather than cooling. Changed precipitation is as commonly a cause of glacial change as is changed temperature.

In particular, the findings of Humwell *et al.* (2005) and Bradwell *et al.* (2006) suggest in some Arctic regions twentieth century air temperatures peaked in the 1930s and 1940s, followed by a cooling that persisted through the end of the century. This thermal behavior is about as different as one could imagine from the steady warming claimed by the IPCC to have occurred around the globe through the twentieth century and especially over the last four decades. That empirical data from the Arctic should contradict this thesis so thoroughly is embarrassing for computer modellers, who have persistently predicted it is the high-latitude regions where anthropogenic global warming should be earliest and most strongly expressed. Clearly the real glacial world is more complex than IPCC computer models allow.

To the degree that in some regions (e.g., the Canadian Arctic) most glaciers have retreated over the past 150 years, this is no more than would be expected for glaciers emerging from the Little Ice Age. This circumstance does not require CO_2 emissions as an additional explanation.

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5.7 The Long Ice Core Record

The large ice sheets of Antarctica and Greenland contain a remarkable record of past climatic changes, accumulated in their layered ice over tens to hundreds of thousands of years (Figure 5.7.1).

These deep ice cores have yielded much critical information about past climatic changes. The $^{18}O/^{16}O$ ratios in the ice can be used to identify past climatic changes, including proxy air temperature; analysis of trapped gases in the ice allows estimation of the ancient CO_2 content of the atmosphere; and fluctuations in the rate of eolian dust influx and other atmospheric parameters can also be determined from the ice.

The ice core data clearly show the climate record is permeated and punctuated by rapid climate changes, including short, abrupt climate swings with surprisingly high rates of warming and cooling (e.g., Steffenssen *et al*., 2008). That the ice core data are indeed a proxy for global climate change is apparent because fluctuations of glaciers all over the world match the climatic events shown in both deep sea mud cores and other ice cores. These results notwithstanding, some scientists remain skeptical of the accuracy of geochemical measurements made in ice cores because of envisaged problems of post-depositional gas migration and ice bubble diffusion, leakage, and fractionation (e.g., Jaworowski *et al.*, 1992).

The most precisely dated ice cores are from the Greenland Ice Sheet Project (GISP) and Greenland Ice Core Project (GRIP). These cores are especially important because the age of the ice at various levels in the core can be measured by counting annual layers in the ice, giving a very accurate chronology. The GISP2 Greenland ice core has proven to be a great source of climatic data from the geologic past. The oxygen isotope ratios of thousands of ice core samples were measured by Minze Stuiver and Peter Grootes at the University of Washington (e.g, Grootes and Stuiver, 1997), and these data have delineated what has become to be accepted as a world standard climatic record.

The ratio of ^{18}O to ^{16}O in an ice core sample depends upon the temperature when the snow crystallized and is later transformed into glacial ice. Ocean volume also may play a role in $\delta^{18}O$ values, but these measurements nonetheless provide a good proxy for ancient temperature, with the age of each sample being accurately known from annual dust layers in the ice core.

Changes in carbon dioxide content lag their equivalent temperature events by between several hundred and 2,000 years in Antarctic ice cores (see Figures 5.7.1 and 5.7.2). Changes in carbon dioxide level cannot be the proximate cause of the warmings and coolings seen. Fischer *et al.* (1999) established CO_2 lagged temperature by 600 ± 400 years as the climate warmed from an ice age. Monnin *et al.* (2001) found warming from the last major ice age preceded rise in CO_2 by 800 ± 600 years. Caillon *et al.* (2003) documented that rise in temperature preceded rise in CO_2 in the Vostok core by 800 ± 200 years. Mudelsee (2001) recognized temperature over the past 420,000 years preceded changes in CO_2 by 1,300 years ± 1,000 in the Vostok core. Petit *et al.* (1999) analyzed 420,000 years of the Vostok core and found as the climate cooled into an ice age, the CO_2 decrease lagged by several thousand years.

Measurements of recent and modern temperature and CO_2 changes show the same lead-lag effect (Figure 5.7.3).

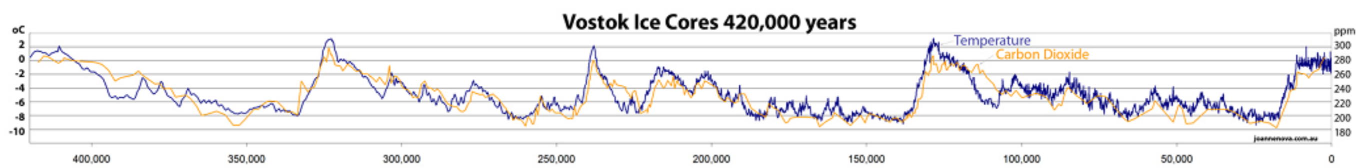

Figure 5.7.1. Temperature and CO_2 for 100,000–150,000 years ago from the Vostock ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. Reprinted from Joanne Nova, 2013, http://joannenova.com.au/global-warming-2/ice-core-graph/.

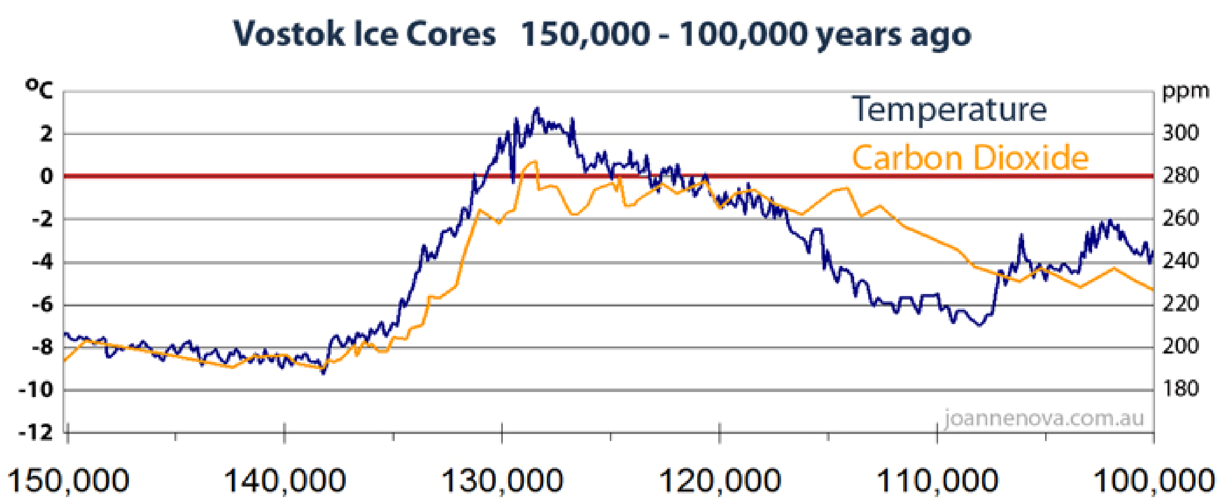

Figure 5.7.2. Temperature and CO_2 levels detail for 100,000-150,000 years ago from the Vostock ice core (Petit *et al.*, 1999; Fischer *et al.*, 1999; Monnin *et al.*, 2001; Caillon *et al.*, 2003. From Joanne Nova, 2013, http://joannenova.com.au/global-warming-2/ice-core-graph/.

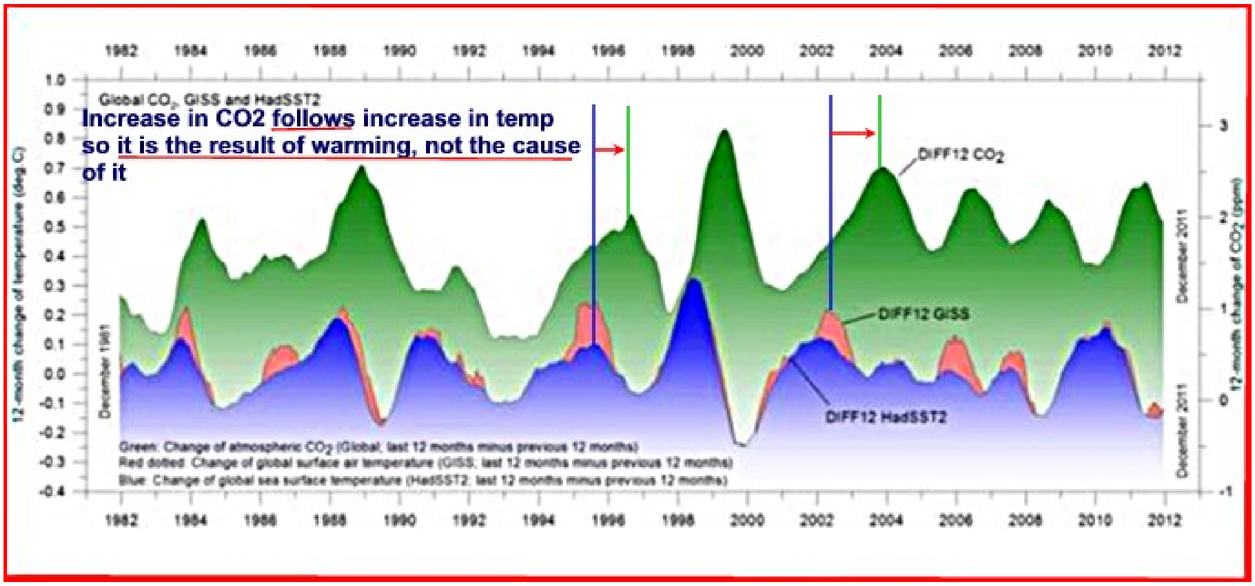

Figure 5.7.3. Lead-lag relationship of increased temperature and increased CO_2 over historic time. Adapted from Humlum, O., Stordahl, J., and Solheim, J. 2012. The phase relation between atmospheric carbon dioxide and global temperature. *Global and Planetary Change* **100**: 51–69. http://dx.doi.org/10.1016/j.gloplacha.2012.08.008.

Conclusion

Changes in atmospheric carbon dioxide levels lag temperature change by at least many hundred years. The studies reviewed here make it clear CO_2 cannot be the cause of the warmings seen in ice cores.

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5.8 Ice-sheet Mass Balance

5.8.1 Through Geological Time

Sixty million years ago, during the warm Paleogene period, Earth possessed no large amounts of ice and no major icecaps. Growth of ice in the Antarctic and Greenland began during a Late Eocene cooling after c. 45 million years ago (Kennett, 1977; Barker *et al.*, 2007; Tripati *et al.*, 2008), though it was probably only in the latest Miocene, c. 10 My ago, that a major northern icecap started to accumulate (Bartoli *et al*., 2005).

Thereafter, global cooling after the latest Pliocene, c. 3 million years ago, resulted in the rapid and progressive growth of large icecaps in both hemispheres to the final sizes they attained during the late Pleistocene. Throughout this process of high-latitude icecap growth, the precise location and size of ice masses depended upon the vicissitudes of local and global climate. Never, for any significant period of time, was a stable, global "ice mass balance" attained, as noted in a recent paper by Naish *et al.* (2009) about the Antarctic ANDRILL project.

The ANDRILL site recovered a marine glacial record for the past 5 million years from the seabed beneath the northwest part of the Ross Ice Shelf. Sedimentary deposition and nearby glacial advance and retreat since the Pliocene have proceeded in sympathy with the background Milankovitch ~40-kyr cyclic variations in insolation controlled by changes in Earth's axial tilt (obliquity). Naish *et al.* state, "the WAIS … periodically collapsed, resulting in a switch from grounded ice, or ice shelves, to open waters in the Ross embayment when planetary temperatures were up to ~3°C warmer than today and atmospheric CO_2 concentration was as high as ~400 ppm" in one especially significant warming episode during marine isotope stage 31 (early Pleistocene, 1.085–1.055 My ago) leading to the deposition of open ocean foraminifer-coccolith-diatom ooze at the Ross Sea drillsite. The extra warm periods during the generally warmer early Pleistocene and Pliocene were clearly not primarily controlled by changes in the air's CO_2 concentration; moreover, the growth (and decay) of ice sheets occurs in response to pervasive climate changes of both deterministic and stochastic nature.

Nothing is more certain than that rhythmic, natural climate fluctuations will continue to occur in the future, and that global ice volume will vary in sympathy. There is therefore no sense in arguments that presume a modern ice mass imbalance, were it to be demonstrated, must be a cause for alarm or attributed to human causation, Nor is there any scientific basis for the common, implicit assumption that the precise global ice balance (or imbalance) that happened to be present before the Industrial Revolution somehow represented conditions of planetary perfection.

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5.8.2 Modern Measurements

Observational data prior to the twenty-first century is for the most part not available to systematically quantify the processes of glacial mass balance. Current satellite and airborne geophysical measuring techniques—InSAR (interferometric synthetic aperture radar); intensity tracking on SAR images; GRACE (Gravity Recovery and Climate Experiment; and ICESat (Ice Cloud, and Land Elevation Satellite)—are in their infancy and often of doubtful accuracy, not least because of the complexity of data processing necessary to render the raw measurements into useful results. In addition, the data sets are so short that they inevitably fail to capture the full range of climatic multidecadal variability.

The GRACE gravity satellite uses radar ranging to measure land ice, a technique requiring accurate knowledge of an appropriate Glacial Isostatic Adjustment (GIA) model. Current GIA calculations for ice sheets are confounded by, among other things, an effect that creates an erroneous conclusion of ice loss when in reality there has been an ice increase (Irvin and James, 2005; Shum *et al.*, 2008; Tegoning *et al.*, 2009; King *et al.*, 2012).

More generally, data from the GRACE satellite have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and other factors. NASA's Jet Propulsion Laboratory is seeking support for the launch of a new space platform, the Geodetic Reference Antenna in Space (GRASP) satellite, the primary mission of which would be to establish an accurate TRF.

The limitations of GRACE interpretations of ice mass balance are well illustrated by two recent papers. The first, by King *et al.* (2012), notes recent estimates of Antarctic ice-mass change cannot be reconciled with each other within the cited formal errors. They cite inadequacy in the models of glacial isostatic adjustment (GIA) as a major cause and adopt a new GIA model with better geological constraints. Applying this model to 2002–2010 GRACE data, King *et al.* estimate a continent-wide ice-mass change of -69 ± 18 Gt/yr. This is about one-third to one-half of other recently published GRACE estimates based on older GIA models (Velicogna, 2009; Chen *et al.*, 2009; Zwartz, 2009), and it represents a +0.19 ± 0.05 mm/yr sea-level change.

Alternatively, Shepherd *et al.* (2012) used "an ensemble of satellite altimetry, interferometry, and gravimetry data sets using common geographical regions, time intervals, and models of surface mass balance and glacial isostatic adjustment to estimate the mass balance of Earth's polar ice sheets" over the period 1992–2011. They estimate the polar ice sheets have contributed 0.59 ± 0.20 mm/yr to the rate of global sea-level rise, driven by individual changes of mass of -142 ± 49 Gt/yr in Greenland, +14 ± 43 Gt/yr in East Antarctica, -65 ± 26 in West Antarctica, and -20 ± 14 Gt/yr in the Antarctic Peninsula.

Notwithstanding the careful and systematic analysis to which the data have been subjected, the uncertainty of these estimates is manifest in the cited error bounds, which range from about 30% to almost 300% of the data value. Further uncertainty as to the relevance of the results is implicit in Shepherd *et al.*'s own caution that "assessments of mass imbalance based on short geodetic records should be treated with care, because fluctuations in surface mass balance can be large over short time periods," not to mention that the time period surveyed represents just one-third of the known 60-year oceanographic cycle.

Until an adequate TRF has been established, papers that use GRACE data, including recent reviews of ice-sheet mass balance like those of King *et al.* (2012) and Shepherd *et al.* (2012), must be viewed as speculative "best interpretations" of the available, noisy data. However, and noting Earth has no intrinsic or "preferred" long-term ice mass balance (as discussed in Section 5.8.1), the fact that as yet we have no way of accurately measuring ice sheet dynamics does not lessen the intrinsic interest of studying historic and modelled changes in the planetary ice budget through time.

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5.8.3 Stability of the Antarctic Ice Sheet

5.8.3.1 Geological setting

The Antarctic ice sheet came into existence a little more than 40 million years ago, during the Eocene, and its size has fluctuated according to climatic conditions. Glacial ice in the Beacon Valley near the Taylor dome of the East Antarctic Ice Sheet lies beneath sediments that contain volcanic ash dated at 8.1 million years, indicating the glacier has existed thoughout the Miocene and Pliocene to the present (Sugden *et al.*, 1995). Even though global temperatures were warmer in the Miocene and Pliocene than in the Quaternary, the Antarctic ice sheet has persisted, albeit at variable extent, for tens of millions of years.

In addition to the extremely cold temperature in Antarctica, a major reason for the stability of the Antarctic ice sheet is the circumpolar vortex, a strong circulation of winds that builds up during the winter months in the upper layers of the atmosphere around Antarctica, effectively isolating the continent from the rest of the world, keeping warm ocean waters away and temperatures low. An analogous circulation system in the ocean, the cold Antarctic Circumpolar Current (ACC), keeps warm sea water away from the Antarctic coast.

As Naish *et al.* (2009) have shown (Section 5.8.1), the Antarctic ice sheet has fluctuated in volume during its evolution, even as it grew progressively through the Plio-Pleistocene to attain its current (interglacial) size. Predictions of its imminent collapse reveal a lack of understanding that isostatic sinking causes both the Greenland and Antarctic icecaps to occupy bedrock depressions; for them to "slide into the sea" would require that they "slide" uphill.

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5.8.3.2 Modern setting

Antarctica holds 91 percent of the world's glacial ice, which is about 73 m of sea-level equivalent (Poore *et al*., 2011), and its melting has the potential to cause major sea-level rise. Whether or not the Antarctic Ice Sheet is melting rapidly is therefore of great importance. News media carry stories nearly every week claiming the Antarctic ice sheet is melting at an accelerating rate and sea level will rise by up to 6 m in coming years. The imminent demise of the Antarctic Ice Cap was what Al Gore apparently had in mind when he warned, if "half of Antarctica melted or broke up and slipped into the sea, sea levels worldwide would increase by between 18 and 20 feet" (Gore 2006).

Ackert (2003) reported some scientists have indeed argued we are witnessing the CO_2-induced "early stages of rapid ice sheet collapse, with potential near-term impacts on the world's coastlines." But empirical evidence for such assertions is thin.

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5.8.3.3 Climatological reality

The average daily temperatures at the South Pole and Vostock, respectively, are -49.4° C (-57° F) and -55.1° C (-67.2° F). To melt any significant amount of Antarctic ice, temperatures would have to rise above the melting point of 0° C. This is not happening now, nor is it likely to happen. Claims of large-scale melting of the Antarctic ice sheet are highly exaggerated. The main Antarctic ice sheet has in fact been cooling since 1957 (see Figure 5.8.3.3.1) and ice accumulation is increasing there rather than decreasing.

The lack of a close network of weather stations in Antarctica makes interpretation of regional temperature distribution difficult. Steig *et al.* (2009) attempted to project temperatures from the West Antarctica Peninsula, where more data are available, to the main Antarctic ice sheet and contended all of Antarctica was warming. That conclusion was hotly disputed by O'Donnell *et al.* (2010), who showed warming over the period of 1957–2006 was concentrated in the West Antarctic Peninsula and the main East Antarctic ice sheet was not warming (Figure 5.8.3.3.2).

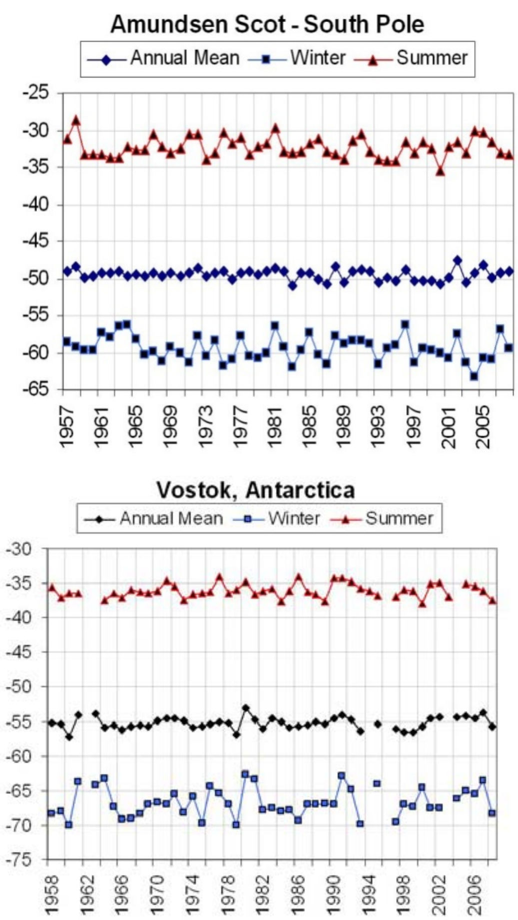

Figure 5.8.3.3.1. Temperature measurements at the South Pole (above) and Vostok (below). Note the lack of any indication of recent warming. Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO_2 emissions as the primary source of global warming.* Elsevier.

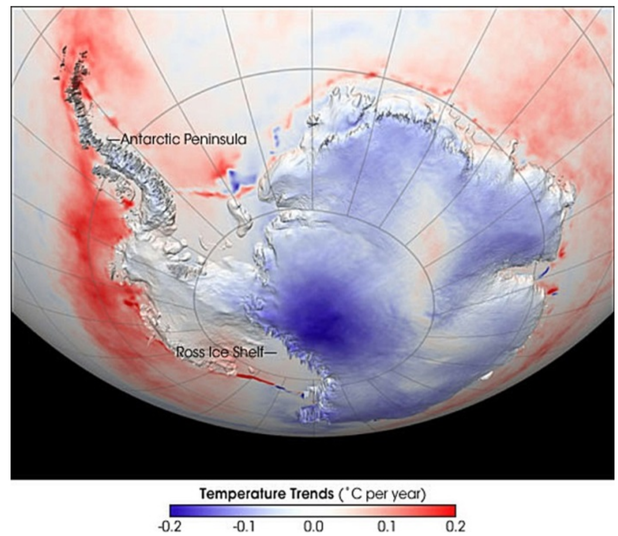

Figure 5.8.3.3.2. Rate of temperature trends in Antarctica between 1982 and 2004. Note almost all of the main East Antarctic Ice Sheet is cooling, not warming, and is not melting. The West Antarctic Peninsula is warmed by ocean currents (red). From National Oceanic and Atmospheric Administration, 2004. Antarctic temperature trend 1982–2004. http://earthobservatory. nasa.gov/IOTD/view.php?id=6502.

The West Antarctic Ice Sheet (WAIS) often has been described as the world's most unstable large ice sheet. As Hillenbrand *et al.* (2002) report, "it was speculated, from observed fast grounding-line retreat and thinning of a glacier in Pine Island Bay (Rignot, 1998; Shepherd *et al.*, 2001), from the timing of late Pleistocene-Holocene deglaciation in the Ross Sea (Bindschadler, 1998; Conway *et al.*, 1999), and from predicted activity of ice-stream drainage in response to presumed future global warming (Oppenheimer, 1998), that the WAIS may disappear in the future, causing the sea-level to rise at a rate of 1 to 10 mm/year (Bindschadler, 1998; Oppenheimer, 1998)."

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5.8.3.4 Modelling studies and mass balance

Modelling studies have addressed how long it might take for extra warmth to bring about a collapse of the WAIS, with Pollard and DeConto (2009) concluding "the WAIS will begin to collapse when nearby ocean temperatures warm by roughly 5°C." Huybrechts (2009) subsequently stated, "the amount of nearby ocean warming required to generate enough sub-ice-shelf melting to initiate a significant retreat of the West Antarctic ice sheet ... may well take several centuries to develop." Once started, he concludes, the transition time for a total collapse of the West Antarctic Ice Sheet would range from "one thousand to several thousand years." This time period, Huybrechts notes, "is nowhere near the century timescales for West Antarctic ice-sheet decay based on simple marine ice-sheet models," as often has been predicted in the past. Thus alarm about the short-term melting of significant volumes of the WAIS is unjustified.

Nevertheless, Gomez et al. (2010) report several studies (Oppenheimer, 1998; Meehl et al., 2007; Vaughan, 2008; Smith et al., 2009) whose authors have suggested "climate change could potentially destabilize marine ice sheets,2 which would affect projections of future sea-level rise." These studies highlight "an instability mechanism (Weertman, 1974; Thomas and Bentley, 1978; Schoof, 2007; Katz and Worster, 2010)" that "has been predicted for marine ice sheets such as the West Antarctic ice sheet that rest on reversed bed slopes, whereby ice-sheet thinning or rising sea levels leads to irreversible retreat of the grounding line."

In contradiction of these fears, Gomez *et al.* present predictions of gravitationally self-consistent sea-level change modeled to follow grounding-line migration, derived by varying the initial ice-sheet size while considering the contribution to sea-level change that derives from various sub-regions of the simulated ice sheet. Their results "demonstrate that gravity and deformation-induced sea-level changes local to the grounding line contribute a stabilizing influence on ice sheets grounded on reversed bed slopes," contrary to earlier assumptions. Rather than destabilizing the ice sheet, Gomez *et al.* concluded, "local sea-level change following rapid grounding-line migration will contribute a stabilizing influence on marine ice sheets, even when grounded on beds of non-negligible reversed slopes."

Zwally and Giovinetto (2011) have provided a thorough review of the differing mass balance estimates for the Antarctic Ice Sheet (AIS) provided in earlier papers and by the IPCC. For the period 1992–2009, they report, estimates of annual mass change fall between values of +50 and -250 Gt/year. This 300 Gt/year range represents about 15 percent of the annual mass input to the AIS, and about 0.8 mm/year sea-level equivalent (SLE). They further note two estimates (+28 and -31 Gt/year) from radar altimeter measurements made by European Remote-sensing Satellites (ERS) lie in the upper part of the

[2] The term "marine ice sheet" appears to refer to icecaps, such as those of Greenland and Antarctica, that are surrounded by and therefore debouch into the ocean.

range, whereas estimates from the Input-minus-Output Method (IOM) and Gravity Recovery and Climate Experiment (GRACE) lie in the lower part (-40 to -246 Gt/year) of the range. By using an alternative method to process the IOM-GRACE data, Zwally and Giovinetto found "the modified IOM and a GRACE-based estimate for observations within 1992–2005 lie in a narrowed range of +27 to -40 Gt/year, which is about 3% of the annual mass input and only 0.2 mm/year SLE."

Zwally and Giovinetto say their preferred estimate for Antarctic mass balance changes for 1992–2001 is -47 Gt/year for West Antarctica, +16 Gt/year for East Antarctica, and -31 Gt/year overall. They expressly report their results do not support the large and increasing rates of mass loss predicted in GRACE-based studies. The potential for large errors to occur in GRACE-based studies, which typically suggest overly large ice losses, has previously been stressed by Ramillien *et al.* (2006), Velicogna and Whar (2006), and Quinn and Ponte (2010). This makes it likely the Zwally and Giovinetto conclusion of a small annual Antarctic ice loss of -31 Gt/year (about 0.1 mm/yr SLE) is probably as accurate a result as it is currently possible to achieve.

Frezzotti *et al.* (2013) present a detailed analysis of the surface mass balance anomaly (SMBA) for Antarctica derived from ice core data. An SMB is a step toward accomplishing a full mass balance, and it is usually defined as the difference at any location between accumulation from solid precipitation (snow) and mass loss from ablation and wind erosion. The total SMB of the grounded AIS is about 2,100 Gt/yr, with a large interannual variability up to 300 Gt/yr (Van den Broeke *et al.*, 2011).

Frezzotti *et al.* show the Antarctic SMB over the past 50 years is not unusual compared with the previous 750 years and falls well within the level of prior natural variations between <50 and >700 $kg/m^2/yr$. They also demonstrate a good correlation exists between temporal variations in SMB and solar activity on the scale of the 200-year de Vries cycle. Beyond these studies, the preparation of the required full mass balance budget for an ice sheet requires accounting for Dynamic Ice Loss (DIL) as well as SMB; DIL, which represents the breakup and melting of the terminus of peripheral or valley outlet glaciers, is a difficult number to estimate accurately (Magand *et al.* 2007; Frezzotti *et al.*, 2007).

Boening *et al.* (2012) point out "an improved understanding of processes dominating the sensitive balance between mass loss primarily due to glacial discharge and mass gain through precipitation is essential for determining the future behavior of the Antarctic ice sheet and its contribution to sea level rise." They set out to assess the causes and magnitude of recent (2009–2011) extreme precipitation events along the East Antarctic coast, using data derived from CloudSat and ERA Interim reanalysis products (Dee *et al.*, 2011).

They found regional mass gain occurred mainly during May 2009 and June 2011, with most of the accumulation occurring in only a few main snowfalls driven by "prolonged changes in pressure patterns and induced poleward wind in the two years." Over the same period, and consistent with their precipitation analysis, GRACE satellite measurements indicate an abrupt mass increase of almost 350 Gt from 2009 to 2011 in East Antarctica along the coast of Dronning Maud Land. This mass increase is equivalent to a decrease in global mean sea level at a rate of 0.32 mm/year.

Putting these results into a longer-term context, Boening *et al.* report the ERA Interim reanalysis data show no significant change in snowfall frequency or strength between 1979 and 2008. Comparing this decadal-scale stability with their finding of abrupt and episodic mass increase in 2009 and 2011, it is apparent stochastic precipitation events can affect regional mass balance in ways that significantly slow the rate of global sea-level rise.

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Earlier research

Other research regarding the stability and natural variation of the WAIS and EAIS is described and discussed in the following papers.

- Bell *et al.* (1998) used airborne geophysical data to study fast-moving ice streams on the WAIS. In conjunction with models, their data suggested a close correlation between the margins of various ice streams and the underlying configuration of sedimentary basins, which in parts appear to act as lubricants for the overlying ice. They conclude, "geological structures beneath the West Antarctic Ice Sheet have the potential to dictate the evolution of the dynamic ice system, modulating the influence of changes in the global climate system," though without indicating how such modulation might work.
- In a review of the WAIS, Bindschadler (1998) analyzed the historical retreat of its grounding line and ice front. Since the Last Glacial Maximum, the retreat of the grounding line occurred faster than its ice front, resulting in an expanding Ross Ice Shelf. Bindschadler reports "the ice front now appears to be nearly stable," although its grounding line may be retreating at a slow rate that would cause dissipation of theWAIS in about 4,000–7,000 years time. Such a retreat, if it occurs, would sustain a sea-level rise of 0.8–1.3 mm/year. Even the slowest of these rates of sea-level rise would require a large negative mass balance for all of West Antarctica, which is not apparent in available data.
- Bindschadler and Vornberger (1998) utilized the available satellite imagery to examine changes of EAIS Ice Stream B, which flows into the Ross Ice Shelf. Since 1963, the ice stream's width has increased by nearly 4 kilometers, at a rate an "order of magnitude faster than models have predicted." However, the authors also report the flow speed of the ice stream decreased over this time period by about 50 percent, noting "such high rates of change in velocity greatly complicate the calculation of mass balance of the ice sheet."
- Oppenheimer (1998) reported on 122 studies

concerned with the stability of the WAIS and its effects on global sea level. He concludes, "human-induced climate change may play a significant role in controlling the long-term stability of the West Antarctic Ice Sheet and in determining its contribution to sea-level change in the near future." Interestingly, however, specific studies Oppenheimer cites provide quite contrary evidence or conclusions. For example, he reports the IPCC "estimated a zero Antarctic contribution to sea-level rise over the past century, and projected a small negative (about -1 cm) contribution for the twenty-first century" and regarding sea-ice extent "the IPCC assessment is that no trend has yet emerged." Regarding the state and behavior of the Antarctic atmosphere and ocean, he also acknowledges "measurements are too sparse to enable the observed changes to be attributed to any such [human-induced] global warming."

Oppenheimer concludes his review with four future scenarios for the WAIS based upon differing assumptions: (1) that the WAIS will collapse suddenly and cause a 4–6 m sea-level rise within the coming century; (2) that the WAIS will gradually disintegrate, with slow sea-level rise over the next two centuries and more rapid disintegration and sea-level rise over the following 200 years; (3) that the WAIS melts over 500–700 years, raising sea level by 6–12 mm/year; and (4) that instead of disintegrating, ice streams slow and the discharge of grounded ice decreases, leading to intra-ice sheet accretion and falling sea level. These scenarios all remain speculative, as Oppenheimer comments, "it is not possible to place high confidence in any specific prediction about the future of WAIS."

- Wingham *et al.* (1998) studied the combined East and West Antarctic ice sheets using satellite radar altimeter measurements from 1992 to 1996 to estimate their rate of change of thickness, and using snowfall variability data from ice cores to calculate a mass balance for the Antarctic ice sheet over the past century. They conclude "a large century-scale imbalance for the Antarctic interior is unlikely," not least because of relative sea level and geodetic evidence suggesting "the grounded ice has been in balance at the millennial scale."
- Anderson and Andrews (1999) analyzed grain size and foraminiferal contents of sediment cores from the eastern Weddell Sea continental shelf and nearby deep-sea floor in an attempt to track the behavior of the East and West Antarctic ice sheets. They found "significant deglaciation of the Weddell Sea continental shelf took place prior to the last glacial maximum," and the ice masses around the Weddell Sea today "are more extensive than they were during the previous glacial minimum." They conclude "the current interglacial setting is characterized by a more extensive ice margin and larger ice shelves than existed during the last glacial minimum, and … the modern West and East Antarctic ice sheets have not yet shrunk to their minimum."
- Conway *et al.* (1999) examined the retreat of the WAIS since its maximum glacial extent 20,000 years ago. They determined the ice grounding line remained near its maximum until about 10,000 years ago, after which it retreated at a rate of about 120 meters per year, this rate also characterizing late twentieth century retreat. The researchers conclude the modern retreat of the WAIS is part of an ongoing recession underway since the early Holocene, and "it is not a consequence of anthropogenic warming or recent sea-level rise." Extrapolating the Holocene retreat rate into the future, a complete and natural deglaciation of the WAIS will occur by about 7,000 years hence.
- Cofaigh *et al.* (2001) analyzed sediment cores from west of the Antarctic Peninsula and the Weddell and Scotia Seas for ice-rafted debris (IRD), seeking an Antarctic analogue of the Heinrich layers of the North Atlantic Ocean, which testify to the repeated collapse of the eastern Laurentide Ice Sheet and discharge of icebergs. Their search was in vain, and the rarity of IRD layers they found "argues against pervasive, rapid ice-sheet collapse around the Weddell embayment over the last few glacial cycles."
- Pudsey and Evans (2001) studied ice-rafted debris obtained from four cores in Prince Gustav Channel, which until 1995 was covered by a floating ice shelf. Their results indicate a retreat of the ice shelf had occurred in the mid-Holocene, since when "colder conditions after about 1.9 ka allowed the ice shelf to reform." In light of this evidence for preindustrial natural change, Pudsey and Evans were careful to state, "we should not view the recent [ice] decay as an unequivocal indicator of anthropogenic climate change." It is likely the breakup of the Prince Gustav Channel ice shelf marks only the culmination of the Antarctic Peninsula's natural recovery from the Little Ice Age.
- Shepherd *et al.* (2001) used satellite altimetry and interferometry to measure the rate of change of the ice thickness of the Pine Island Glacier drainage basin, WAIS, between 1992 and 1999. The grounded glacier thinned at a constant rate of 1.6 m/year, and this "thinning cannot be explained by short-term variability in accumulation and must result from

glacier dynamics." Because glacier dynamics typically respond to phenomena operating on time scales of hundreds to thousands of years, this observation argues against twentieth century warming being a primary cause of the thinning; instead, a long-term phenomenon of considerable inertia must be at work in this particular situation.

- Hillenbrand *et al.* (2002) undertook studies of sediment cores from the Amundsen Sea, West Antarctica, a site likely to be sensitive to environmental changes related to WAIS collapse. They found all proxies sensitive to collapse changed markedly during the global climatic cycles of the past 1.8 million years, but at no level was evidence found for a Pleistocene disintegration of the WAIS. The authors remark their results "suggest relative stability rather than instability of the WAIS during the Pleistocene climatic cycles," a conclusion "consistent with only a minor reduction of the WAIS during the last [warmer] interglacial period." A similar conclusion was reached by Huybrechts (1990), Cuffey and Marshall (2000), and Huybrechts (2002).
- In another paper addressing possible WAIS collapse, O'Neill and Oppenheimer (2002) speculate the ice sheet "may have disintegrated in the past during periods only modestly warmer (~2°C global mean) than today," thereby claiming that setting "a limit of 2°C above the 1990 global average temperature"—above which the mean temperature of the globe should not be allowed to rise—"is justified." We are aware of no empirical evidence to support this claim.
- Raymond (2002) presents a brief appraisal of the status of the world's major ice sheets. Relative to the WAIS, he concludes "substantial melting on the upper surface of WAIS would occur only with considerable atmospheric warming." In a summary statement taking account of the available observations, Raymond writes "the total mass of today's ice sheets is changing only slowly, and even with climate warming increases in snowfall should compensate for additional melting," such as might occur for the WAIS if the planet's temperature should resume its post-Little Ice Age warming.
- Stone *et al.* (2003) used cosmogenic ^{10}Be exposure dates of glacially transported cobbles in elevation transects on the Ford Ranges, western Marie Byrd Land, to reconstruct a history of ice-sheet thinning over the past 10,000-plus years. They conclude "the exposed rock in the Ford Ranges, up to 700 m above the present ice surface, was deglaciated within the past 11,000 years," and evidence also suggests the maximum ice sheet stood considerably higher than this. Comparing the age of exposure with site elevation "indicates steady deglaciation since the first of these peaks emerged from the ice sheet some time before 10,400 years ago" and demonstrates the mass balance of the region has been negative throughout the Holocene. They conclude it is clear that West Antarctic deglaciation continued long after the disappearance of the Northern Hemisphere ice sheets, and may still be under way.
- Davis and Ferguson (2004) evaluated elevation changes of the Antarctic ice sheet for 1995–2000, measured by radar altimetry from the European Space Agency's European Remote Sensing 2 satellite. They found the East Antarctic Ice Sheet had a five-year trend of 1.0 ± 0.6 cm/year, the West Antarctic Ice Sheet a five-year trend of -3.6 ± 1.0 cm/year, and the entire Antarctic continent a five-year trend of 0.4 ± 0.4 cm/year. Melting was apparent in the Pine Island, Thwaites, DeVicq, and Land glaciers of West Antarctica, which exhibited five-year trends ranging from -26 to -135 cm/year, and this was interpreted as resulting from stronger glacial flow caused by warm ocean temperatures having enhanced basal melting.
- In 2005, the journal *Climatic Change* published an editorial essay by Oppenheimer and Alley, who discussed "the degree to which warming (of the Antarctic and Greenland ice sheets) can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other." In their opinion, the key questions with respect to both ice sheets were "What processes limit ice velocity, and how much can warming affect those processes?" Commenting that no scientific consenus exists on the answers, they identify 14 areas in which our knowledge of the matter remains uncertain (Table 1), reflecting both the weakness of current models and the uncertainty in paleoclimatic reconstructions. Oppenheimer and Alley identify this list of deficiencies of knowledge as "gaping holes in our understanding."
- Velicogna and Wahr (2006) used measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the period 2002–2005. They conclude "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/year of ice, equivalent to 0.4 ± 0.2 mm/year of global sea-level rise." The mass loss came entirely from the WAIS; the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year. Velicogna and Wahr

- concede there is both ambiguity and geophysical contamination caused by signals from outside Antarctica, including continental hydrology and ocean mass variability. The GRACE mass solutions "do not reveal whether a gravity variation over Antarctica is caused by a change in snow and ice on the surface, a change in atmospheric mass above Antarctica, or post-glacial rebound (PGR: the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years)." These estimates and adjustments are convoluted and complex, as well as highly dependent upon various models. Velicogna and Wahr acknowledge "the PGR contribution is much larger than the uncorrected GRACE trend" (by a factor of almost five), and "a significant ice mass trend does not appear until the PGR contribution is removed." Clearly these results apply to too short a period of time, and are too model-dependent, to be useful.
- van de Berg *et al.* (2006) compared results of model-simulated Antarctic surface mass balance (SMB) and all available mass balance observations to construct "a best estimate of contemporary Antarctic SMB." SMB data was derived from Vaughan *et al.* (1999), van den Broeke *et al.* (1999), Frezzotti *et al.* (2004), Karlof *et al.* (2000), Kaspari *et al.* (2004), Magand *et al.* (2004), Oerter *et al.* (1999, 2000), Smith *et al.* (2002), and Turner *et al.* (2002). The measurements included moving surficial stake arrays, location of atom bomb geochemical tracer horizons, and chemical analyses of ice cores.

  van de Berg *et al.* determined "the SMB integrated over the grounded ice sheet (171 ± 3 mm per year) exceeds previous estimates by as much as 15%." Their results differ by more than a meter per year higher in coastal areas of both East and West Antarctica.
- In another altimeter study, Wingham *et al.* (2006) utilized European remote sensing satellite measurements to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. Their measurements covered 72 percent of the area of the grounded ice sheet. After correction for isostatic rebound, these authors found the ice sheet to be growing at 5 ± 1 mm per year. This translates to the ice sheet gaining 27 ± 29 Gt of ice per year, which would lower global sea level by 0.08 mm per year.
- Ramillien *et al.* (2006) provided new estimates of the mass balances of the East and West Antarctic ice sheets from GRACE data for the period 2002–2005, identifying a mass loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East

Table 1.
Summary Points from the Oppenheimer and Alley (2005) review

Regarding the Antarctic and Greenland ice sheets, we do not know:

i. If the apparent response of glaciers and ice streams to surface melting and melting at their termini (e.g., ice shelves) could occur more generally over the ice sheets.

ii. If dynamical responses are likely to continue for centuries and propagate further inland, or if it is more likely they will be damped over time.

iii. If surface melting could cause rapid collapse of the Ross or Filchner-Ronne ice shelves, as occurred for the smaller Larsen ice shelf.

iv. If ice sheets made a significant net contribution to sea-level rise over the past several decades.

v. What might be useful paleoclimate analogs for sea level and ice sheet behavior in a warmer world.

vi. The reliability of Antarctic and Southern Ocean temperatures (and polar amplification) projected by current GCMs, nor do we know why they differ so widely among models, nor how these differences might be resolved.

vii. The prospects for expanding measurements and improving models of ice sheets, nor the timescales involved.

viii. If current uncertainties in future ice sheet behavior can be expressed quantitatively.

ix. What would be useful early warning signs of impending ice-sheet disintegration nor when these might be detectable.

x. Given current uncertainties, if our present understanding of the vulnerability of either the WAIS or GIS is potentially useful in defining "dangerous anthropogenic interference" with Earth's climate system.

xi. If the concept of a threshold temperature is useful.

xii. If either ice sheet seems more vulnerable, and thus should provide a more immediate measure of climate "danger" and a more pressing target for research.

xiii. If any of the various temperatures proposed in the literature as demarcating danger of disintegration for one or the other ice sheet is useful in contributing to a better understanding of "dangerous anthropogenic interference."

xiv. On what timescale future learning might yield the answers to these questions.

- Antarctica, resulting in an average net ice loss for the entire continent of 40 km^3/year and a sea-level rise of 0.11 mm/year. This result is of the same order of magnitude as the 0.08 mm/year Antarctic-induced mean sea-level rise calculated by Zwally *et al.* (2005), which was derived from nine years of satellite radar altimetry data from the European Remote-sensing Satellites ERS-1 and -2. However, and as Ramillien *et al.* concede, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."
- Remy and Frezzotti (2006) review the three principal ways by which ice sheet mass balance is estimated: by measuring the difference between mass input and output, by monitoring the changing geometry of the continent, and by modeling the dynamic and climatic evolution of the continent. The researchers conclude "the East Antarctica ice sheet is nowadays more or less in balance, while the West Antarctica ice sheet exhibits some changes likely to be related to climate change and is in negative balance." They also report "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale," which they describe in terms of centuries.
- Van den Broeke *et al.* (2006) employed a regional atmospheric climate model (RACMO2), with snowdrift-related processes calculated offline, to calculate the flux of solid precipitation (Ps), surface sublimation (SU), sublimation from suspended (drifting/saltating) snow particles, horizontal snow drift transport, and surface melt (ME). Having found a good match between the model output and observations, and after analyzing the data-driven results for trends over the period 1980–2004, the researchers report "no trend is found in any of the Antarctic SSMB components, nor in the size of ablation areas."
- Krinner *et al.* (2007) used the LMDZ4 atmospheric general circulation model (Hourdin *et al.*, 2006) to simulate Antarctic climate for the periods 1981–2000, to test the model's ability to adequately simulate present conditions, and 2081–2100, to see what the future might hold. They conclude "the simulated present-day surface mass balance is skilful on continental scales," which gives them confidence regarding their mass balance projections for the end of the twenty-first century. The projections indicate by that time "the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year," which corresponds to a sea-level decrease of 1.2 mm per year by the end of the century and a cumulative sea-level decrease of about 6 cm. The simulated temperature increase causes increased moisture transport toward the interior of the continent where the moisture falls as snow, causing the continent's ice sheet to grow.

Conclusions

Several arguments contradict the idea that human-caused global warming is putting Antarctica under threat of massive ice loss with attendant effects on local environments and global sea-level rise.

First, the mild warming witnessed in the late twentieth century was well within the bounds of natural variation and now has ceased: Global average temperature has not increased since at least 1996. The warming that is assumed to drive the system, and in particular all of the model studies, is no longer occurring.

Second, and even if warming were still occurring, the results of Krinner *et al.* (2007) suggest the likely regional response is enhanced moisture flow into the icecap interior, leading to increased snowfall and ice accumulation; i.e., an increasingly positive mass balance.

Third, despite the last few interglacials being warmer than the Holocene by 2–5^{O} C (Petit *et al.*, 1999), several studies have found sediment cores adjacent to Antarctica provide no evidence of any dramatic breakups of the WAIS over the past few glacial cycles. With or without resumed global warming, there is therefore no reason to expect changes in the Antarctic icecap other than those that happen naturally. Furthermore, we know throughout the long central portion of the current interglacialm when the most recent peak Antarctic temperature was reached, it was much warmer than it was in the late twentieth century, yet no evidence exists of even a partial WAIS disintegration at that time. The Antarctic ice sheet also appears to have been impervious to the effects of the climate change that characterized the Medieval Warm Period and Little Ice Age. Representing, as they do, the 1,500-yr Bond rhythm, these types of events—and specifically, a new Little Ice Age—are the most likely significant external major forcing agents that will confront Antarctica over the next 1,000 years.

Fourth, though most mass balance calculations are based upon the shifting sands of computer modeling, the evidence so far indicates West

Antartica is warming and losing significant ice mass, and East Antarctica is cooling and accreting ice. The sum of that evidence indicates the whole Antarctic icecap is close to mass balance (Zwally and Giovenetto, 2011). As Davis and Ferguson (2004) have shown, and driven by the significantly positive trend of the much larger East Antarctic ice sheet, the ice volume of Antarctica increased over the last five years of the twentieth century, driven by increased snowfall.

Fifth, many of the most cited papers on Antarctica involve complex computer modeling and applying the GRACE gravity data and a contemporary geoid model, both of which are highly uncertain. The modeling study of Krinner *et al.* (2007) demonstrated an impressive ability to reconstruct past mass balance changes over the late twentieth century and may therefore perhaps be viewed with a little more confidence than most other similar studies. The projections of this model out to 2100, and based upon continuing warming, are for increased ice accretion across Antarctica. Thus, at least one successful model predicts CO_2-induced global warming, should it occur, will actually buffer the world against the much-hypothesized catastrophic loss of ice mass from the polar icecaps and also against the feared impact of ice-melt-driven sea-level rise.

Sixth, and finally, several studies, for example from Marie Byrd Land and in Pine Island Bay, have demonstrated a pattern of steady Holocene ice retreat that occurred at rates similar to modern retreat. The authors of these studies have concluded this retreat is simply a manifestation of the slow but steady deglaciation taking place ever since end of the last great ice age. As Ackert (2003) states, "recent ice sheet dynamics appear to be dominated by the ongoing response to deglacial forcing thousands of years ago, rather than by a recent anthropogenic warming or sea-level rise." Therefore, and as Anderson and Andrews (1999) have shown, the great inertial forces at work over the millennia suggest parts of the East and West Antarctic Ice Sheets will continue to slowly wane and release icebergs to the Southern Ocean over the coming years, decades, and centuries quite independent of short-term changes in global air temperature.

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5.8.4 Stability of the Greenland Ice Sheet

The Greenland ice sheet is the second largest ice mass in the world (Figure 5.8.4.1). It is 2,400 km long and 1,100 km wide at its widest point, covering 1,710,000 km^2. The mean altitude of the ice surface is 2,135 m, and the ice is up nearly 3 km thick in central Greenland. The lowest mean annual temperatures are about -31°C. Because the Greenland ice sheet is not a polar glacier, meltwater occurs at the base of the glacier, which facilitates basal sliding. The ice sheet margin reaches the sea only in limited areas, so no large ice shelves occur. Large outlet glaciers flow through deep fiords around the periphery of Greenland and calve off into the ocean, producing numerous icebergs.

Many claims are made that melting of the Greenland ice sheet during the post-1977 warm period occurred at an unprecedented or extreme rate, and that in consequence damaging sea-level rise would occur. These claims seldom are tested against known climatic records. Past temperature records (Figure 5.8.4.2) show Greenland has followed a predictable pattern of multidecadal warming and cooling over the past century. Ice volume also has waxed and waned, following both global temperatures and the warming/cooling patterns in the oceans (Chylek *et al.*, 2004, 2006). Greenland's history includes two periods of cooling and two periods of warming over the past 100 years, with the warmest year being 1941 and the warmest decades being the 1930s and 1940s.

The most recent (post-1977) Arctic warming and resultant increased ice melt were not at all unusual. Kobashi *et al.* (2011) provide a longer, 2,000-year long context for these historical measurements (Figure 5.8.4.3). They reconstructed Greenland surface snow temperature variability at the GISP2 site using argon and nitrogen isotopic ratios (δ^{15}N, δ^{40}Ar) from air bubbles in the core, finding the average Greenland snow temperature over the past 4,000 years has been -30.7°C with a standard deviation of 1.0°C. In comparison, the current decadal average surface temperature (2001–2010) at the GISP2 site is -29.9°C. Similar results have been achieved using the borehole temperature inversion technique by Dahl-Jensen *et al.* (1998).

The reconstructed Greenland temperature from 1845 to1993 correlates well with the 10-year running mean Summit temperature (Box *et al.*, 2009), these results confirming the reliability of the Kobashi *et al.* (2011) reconstruction. Current decadal temperatures in Greenland clearly do not exceed the envelope of natural variability over the past 4,000 years.

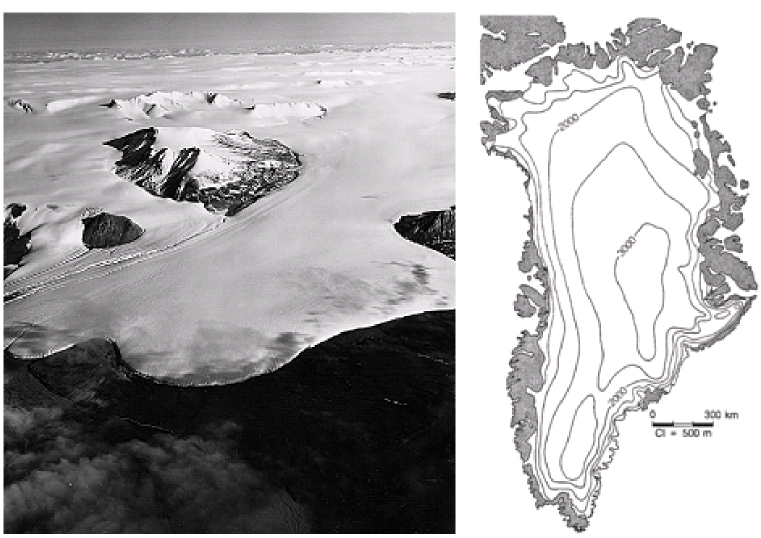

Figure 5.8.4.1. LEFT. Greenland ice sheet (Photo by Austin Post). RIGHT. Contours on the surface of the Greenland ice sheet. Adapted from Easterbrook, D.J. 1993. *Surface processes and landforms.* Prentice Hall.

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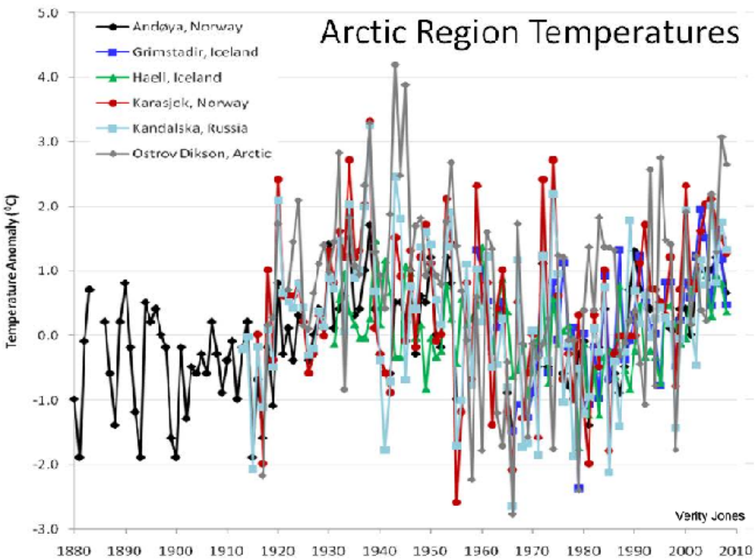

Figure 5.8.4.2. Arctic temperatures from 1880 to 2010. Adapted from Chylek, P., Box, J.E., and Lesins, G. 2004. Global warming and the Greenland ice sheet. *Climatic Change* **63**: 201–221; Chylek, P., Dubey, M.K., and Lesins, G. 2006. Greenland warming of 1920–1930 and 1995–2005. *Geophysical Research Letters* **33**: 10.1029/ 2006GL026510.

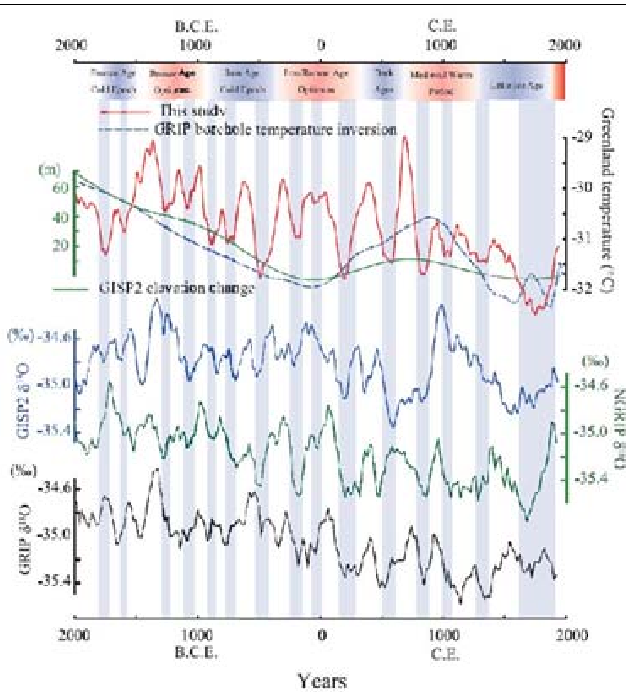

Figure 5.8.4.3. Reconstructed Greenland temperatures compared with oxygen isotope ratios (GISP2, GRIP, and NGRIP) for the past 2,000 years. Adapted from Kobashi, T., Kawamura, K., Severinghaus, J.P., Barnola, J.-M., Nakaegawa, T., Vinther, B.M., Johnsen, S.J., and Box, J.E. 2011. High variability of Greenland surface temperature over the past 4000 years estimated from trapped air in an ice core. *Geophysical Research Letters* **38**: L21501, doi:10.1029/2011GL049444.

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Other research

Other recent research relevant to the mass balance of the Greenland Ice Cap includes the following papers:

- From long temperature records from southern Greenland, Godthab Nuuk on the west coast and Ammassalik on the east coast, Chylek *et al.* (2006) found "although the whole decade of 1995–2005 was relatively warm, the temperatures at Godthab Nuuk and Ammassalik were were not exceptionally high," and "almost all decades between 1915 and 1965 were warmer than, or at least as warm as, the 1995 to 2005 decade, indicating that the current warm Greenland climate is not unprecedented and that similar temperatures were the norm in the first half of the 20th century." They note "two periods of intense warming (1995–2005 and 1920–1930) are clearly visible in the Godthab Nuuk and Ammassalik temperature records," but "the average rate of warming was considerably higher within the 1920–1930 decade than within the 1995–2005 decade."

Chylek *et al.* (2006) note, "An important question is to what extent can the current (1995–2005) temperature increase in Greenland coastal regions be interpreted as evidence of man-induced global warming?" They conclude, "The Greenland warming of 1920 to 1930 demonstrates that a high concentration of carbon dioxide and other greenhouse gases is not a necessary condition for a period of warming to arise," and "the observed 1995–2005 temperature increase seems to be within the natural variability of Greenland climate."

- Ettema *et al.* (2009) state "to better quantify and predict the mass balance and freshwater discharge of the Greenland Ice Sheet requires improved knowledge of its surface mass balance (SMB)," defined as the annual sum of mass accumulation (snowfall, rain) and ablation (sublimation, runoff). They apply a regional atmospheric climate model over the Greenland Ice Sheet and its surrounding oceans and islands at the unprecedented high horizontal resolution of ~11 km, coupled to a physical snow model that treats surface albedo as a function of snow/firn/ice properties, meltwater percolation, retention, and refreezing. The atmospheric part of the model was forced at the lateral boundaries and the sea surface by the global model of the European Centre for Medium-Range Weather Forecasts for the period September 1957 to September 2008.

The model projected an annual precipitation for the Greenland ice sheet for 1958–2007 that was up to 24 percent higher, and a surface mass balance that was up to 63 percent higher, than previously thought. The GIS's SMB averaged 469 ± 41 Gt/year over the study period. Before 1990, none of the mass balance components exhibited a significant trend, but after 1990 a slight downward trend of 12 ± 4 Gt/year occurred in SMB. Though lacking the context of a full mass balance for Greenland, Ettema *et al.* still felt able to conclude, "considerably more mass accumulates on the Greenland Ice Sheet than previously thought," adjusting earlier estimates upwards by as much as 63 percent.

- Sundal *et al.* (2011) report on five years of satellite observations (1993, 1995–1998) of ice motion in southwest Greenland. As in previous studies, they found although peak ice flow speeds are positively correlated with the degree of melting, mean summer flow rates are not. This is because glacier slow-down usually occurs only when a critical run-off threshold of about 1.4 cm/day is exceeded. In the first half of summer, flow is similar in all years, but increased flow during later summer is 62 ± 16 percent less in warmer years. Accordingly, in warmer years "the period of fast ice flow is three times shorter and, overall, summer ice flow is slower." Sundal *et al.* concluded, perhaps counterintuitively but as van de Wal *et al.* (2008) showed earlier, "a long-term (17-year) decrease in Greenland's flow [occurred] during a period of increased melting."

- Bjork *et al.* (2012) used data gathered by the seventh Thule Expedition (Gabel-Jorgensen, 1935, 1940), which surveyed the southeast coast of Greenland in 1932–1933, comparing the data with later aerial photographs and satellite images in order to study glacial behavior between 1932 and 2010. The terminus regions of 132 glaciers along more than 600 km of the southeast Greenland coastline were included in the study.

Two significant glacier recessional events were identified, one during the 1930s (1933–1943) and another during the 2000s (2000–2010), accompanied by increasing temperatures. Marine-terminating glaciers retreated more rapidly during the recent warming, which was otherwise manifest in similar ways to the 1930s warming—in fact, "many land-terminating glaciers underwent a more rapid retreat in the 1930s than in the 2000s." Bjork *et al.* point out the recent high rate of retreat may slow when retreating marine-terminating glaciers reach their grounding line and become less sensitive to the influence of ocean temperature (Howat *et al.*, 2008; Moon and Joughin, 2008), and positive or negative feedback mechanisms relating to the cold East Greenland Coastal Current may also come into play (Murray *et al.*, 2010).

- Bergmann *et al.* (2012) reevaluated GIS mass balance over the longer timespan of 2002–2010, using what they view as improved post-processing techniques. They found a decreasing mass loss of the GIS over the last few years for all the considered sources (UTCSR, GFZ, and JPL) and several filtering methods (Gaussian and Gaussian + ICA for averaging radii of 300, 400, and 500 km). Bergmann *et al.* report "the increase in snowfall since winter 2008–2009 in the south and since 2009–2010 in the north, and also a deceleration of the glacier discharge since 2008 reported in several studies using independent data, are responsible for the decrease in mass loss of Greenland."

- Kjaer *et al.* (2012) used a digital elevation model derived from aerial photographs to extend the record of Dynamic Ice Loss for northwestern Greenland back to 1985. They describe two independent dynamic ice loss events, one extending from 1985 to 1993 and the other from 2005 to 2010, separated by periods of relative ice stability ("limited mass changes"). The ice mass changes were caused primarily by short-lived dynamic ice loss events rather than by changes in the surface mass balance, which, as Kjaer *et al.* point out, "challenges predictions about the future response of the Greenland Ice Sheet to increasing global temperatures."

Conclusions

As for Antarctica, though perhaps to a lesser degree, the mass balance of the Greenland Ice Sheet (GIS) is of high interest in the context of global warming because the IPCC projects melting of the whole ice sheet would contribute nearly 7 meters to sea-level rise (Bergmann *et al.*, 2012).

Predicting the sea-level response that will occur as a result of changes in the global cryosphere requires an accurate knowledge of the present-day and recent-past mass balance for the major icecaps and glaciers throughout the world as well as a prediction of the stability through time of present-day mass balances. Prior to the availability of satellite measurements, the mass balances of the major ice sheets were poorly known.

Even today, representing these matters accurately remains a difficult task because of the variety and complexity of the processes that control the accumulation and destruction of glacial ice, and because of inadequacies in our measuring systems (Section 5.8.2 above).

The literature summarized above makes clear no empirical evidence yet exists for unusual or unnatural temperature or ice volume changes on the Greenland ice sheet.

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Earlier research

Other evidence regarding the stability and natural variation of the Greenland ice sheet is described and discussed in the following earlier research papers.

- Krabill *et al.* (2000) used aircraft laser-altimeter surveys over northern Greenland in 1994 and 1999, together with previously reported data from southern Greenland, to evaluate the mass balance of the Greenland Ice Sheet. Above an elevation of 2,000 meters they found areas of both thinning and thickening, and these phenomena nearly balanced each other, so that in the south there was a net thinning of 11 ± 7 mm/year, while in the north there was a net thickening of 14 ± 7 mm/year. The region exhibited a net thickening of 5 ± 5 mm/year; but after correcting for bedrock uplift, which averaged 4 mm/year in the south and 5 mm/year in the north, the average thickening rate decreased to practically nothing. Krabill *et al.* described the net balance as "zero."

At lower elevations, thinning predominated along approximately 70 percent of the coast. Here, however, data were so sparse (widely spaced flight lines) that the researchers acknowledged, "in order to extend our estimates to the edge of the ice sheet in areas not bounded by our surveys, we calculated a hypothetical thinning rate on the basis of the coastal positive degree day anomalies." They then interpolated between this calculated coastal thinning rate and the nearest observed elevation changes to obtain their final estimate of mass balance, a net reduction in ice volume of 51 km^3/year. Acknowledging the uncertainty of this result, Krabill *et al.* note changes in ice dynamics, rather than changes in temperature, were the most likely cause of the hypothetical ice sheet thinning.

- Taurisano *et al.* (2004) describe the temperature trends of the Nuuk Fjiord, West Greenland, during the past century, in order to assess the local glacial dynamics. Their data show a warming trend for the first 50 years of the 1900s, followed by cooling over the second part of the twentieth century, when the average annual temperatures decreased by approximately 1.5°C. The cooling was accompanied by "a remarkable increase in the number of snowfall days (+59 days)" and affected the summer mean as well as winter temperatures but was not accompanied by any significant change in annual precipitation. Comparison with regional data led Taurisano *et al.* to conclude the Nuuk Fjiord climatic history is similar to that recorded at many other stations throughout south and west Greenland (cf. Humlum, 1999; Hanna and Cappelen, 2002, 2003).
- Zwally *et al.* (2005) used satellite radar altimetry to determine the Greenland Ice Sheet is "growing inland with a small overall mass gain," while thinning at the margins. Similarly, Johannessen *et al.* (2005) found for the 11-year period 1992–2003 the elevation-change rate below 1,500 meters was [negative] 2.0 ± 0.9 cm/year, but "an increase of 6.4 ± 0.2 cm/year is found in the vast interior areas above 1500 meters." Spatially averaged over the whole ice sheet, this results in a net increase of 5.4 ± 0.2 cm/year (~60 cm over 11 years, or ~54 cm when corrected for isostatic uplift). Zwally *et al.* conclude the GIS experienced no net loss of mass for the decade after 1992, but instead theoretically contributed a 0.03 ± 0.01 mm/year decline in sea level.
- Rignot and Kanagaratnam (2005) used satellite radar interferometry observations of Greenland to detect what they called "widespread glacier acceleration." Calculating this phenomenon had led to a doubling of the ice sheet mass deficit in the past decade and, therefore, a comparable increase in Greenland's contribution to rising sea levels, they claim "as more glaciers accelerate ... the contribution of Greenland to sea-level rise will continue to increase."

The problem with this conclusion is that instead of using measurements for their evaluation, Rignot and Kanagaratnam used modeled estimates by Hanna *et al.* (2005), who used meteorological models "to retrieve annual accumulation, runoff, and surface mass balance." When actual measurements of the ice sheet via satellite radar altimetry are employed, a different result is reached—one of near mass balance, as indicated by the work of Zwally *et al.* (2005), Johannessen *et al.* (2005), and others.

- Nick *et al.* (2009) made a comprehensive study of the outlet glaciers that occur around the margins of the Greenland Ice Sheet. They report a recent marked retreat, thinning, and acceleration of most of Greenland's outlet glaciers south of 70°N, which, given it paralleled a temperature rise, raises concern over future sea-level rise.

To better understand this ice history, the authors developed a numerical ice-flow model to reproduce the changes in one of the largest outlet glaciers, the Helheim Glacier. The model simulations suggest ice acceleration, thinning, and retreat begin at the calving glacier terminus, and then propagate upstream through dynamic coupling along the glacier.

- Sharp and Wang (2009) used scatterometer data to map the timing of the 2000–2004 annual melt and freeze-up on three Eurasian icecaps east of Greenland: Svalbard [Norway], Novaya Zemlya [Russia], and Severnaya Zemlya [Russia].Their five-year study was placed in context by developing regression relationships between melt season duration and annual (June + August) mean 850-hPa air temperature over each region (from NCEP-NCAR Reanalysis) that could be used to predict the annual melt duration for each year in the 1948–2005 period. The 2000–2004 pentad has the second-longest mean predicted melt duration on Novaya Zemlya (after 1950–1954), and the third longest on Svalbard (after 1950–1954 and 1970–1974) and Severnaya Zemlya (after 1950–1954 and 1955–1959), with respect to all discrete five-year periods between 1950 and 2004.
- Wake *et al.* (2009) also attempted to assess the rapidity of Greenland ice melt, using a surface mass balance model. The authors reconstructed the 1866–2005 surface mass-balance (SMB) history of the Greenland ice sheet on a 5 x 5 km grid, using a runoff-retention model based on the positive degree, which they forced with data sets of temperature and precipitation dating back to 1866. They sought to compare "the response of the ice sheet to a recent

period of warming and a similar warm period during the 1920s to examine how exceptional the recent changes are within a longer time context."

The model outputs suggested present-day SMB changes "are not exceptional within the last 140 years," with the SMB decline over 1995–2005 being no different from that of 1923–1933. Wake *et al.* conclude the recent and extensively monitored SMB changes (Krabill *et al.*, 2004; Luthcke *et al.*, 2006; Thomas *et al.*, 2006) "represent natural sub-decadal fluctuations in the mass balance of the ice sheet and are not necessarily the result of anthropogenic-related warming."

- In keeping with these earlier findings, Murray *et al.* (2010) report the Greenland Ice Sheet's annual ice discharge doubled during the 2000s, accompanied by outlet glacier thinning, accelerating, and retreating. This phase of fast discharge was followed by slowdown, for in 2006 two of the largest glaciers in the sector, Helheim and Kangerdlugssuaq, slowed down simultaneously (Howat *et al.*, 2007), ceased thinning (Stearns and Hamilton, 2007; Howat *et al.*, 2007), and even readvanced (Joughin *et al.*, 2008). Other nearby glaciers behaved in similar fashion (Howat *et al.*, 2008; Moon and Joughin, 2008), making the slowdown from 2006 widespread, synchronized throughout southeast Greenland, and lasting until at least 2008.

Conclusions

Arguments similar to those offered in discussing the impact of global warming on Antarctic ice mass-balance (Section 5.8.3 above) apply also to Greenland. However, much longer instrumental temperature records exist for Greenland than Antarctica, and these show beyond doubt that previous natural warming cycles at least equalled, and more probably exceeded, the mild warming at the end of the twentieth century.

In addition, several Greenland studies have stressed ice mass balance change often results from internal dynamics, and no simple relationship exists between glacial melt and increasing temperature. For example, in studying the Helheim and nearby glaciers, Nick *et al.* (2009) concluded their modeling showed "tidewater outlet glaciers should adjust extremely rapidly to changing boundary conditions at the calving terminus, which indicates that the recent rates of mass loss in Greenland's outlet glaciers are a transient phenomenon, and should not be extrapolated into the future."

Despite concerns expressed about global warming becoming increasingly intense in its effects in the Arctic over the past two decades, conditions during the middle of the twentieth century seem to have been in this respect even more extreme than at any subsequent time, especially on the icecaps and associated glaciers studied by Sharp and Wang (2009), who concluded "the 1950–54 pentad … experienced the longest melt season of the past 55 years on all three of the large Eurasian Arctic ice caps."

Meanwhile, many of Greenland's outlet glaciers debouch directly into the ocean, which makes the work of Murray *et al.* (2010) particularly pertinent. They conclude an oscillatory mechanism is at work, whereby increasing ice wastage flow causes glacial termini to push out into warmer ocean water, there melting to enhance the rate of cold water input into the East Greenland Coastal Current, thus in turn weakening its melting capacity. Murray *et al.* conclude their research suggests the presence of "a negative feedback that currently mitigates against continued very fast loss of ice from the ice sheet in a warming climate," noting "we should expect similar speedup and slowdown events of these glaciers in the future, which will make it difficult to elucidate any underlying trend in mass loss resulting from changes in this sector of the ice sheet."

Ettema *et al.* (2009) recently concluded "considerably more mass accumulates on the Greenland Ice Sheet than previously thought," adjusting upwards earlier estimates by as much as 63 percent, which suggests the Northern Hemisphere's largest ice sheet is not in imminent danger of disintegration.

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5.9 Mountain Glaciers

Over periods of decades to millennia, most valley glaciers' ice either extends in length down-valley (meaning accumulation must be exceeding melting), or shrink in size or retreat up-valley (meaning melting must be exceeding accretion).

5.9.1 Holocene glacial history

Few quantitative observations of glacier extent exist prior to about 1860, though inferences about earlier advances and retreats can be made from paintings, sketches, and historical documents. Fossil wood, *in situ* tree stumps, and human artifacts and dwellings indicate in earlier historic times glaciers in the European Alps were smaller and situated farther up their valleys.

Glacier retreat has not been constant over the past several centuries. Instead, glaciers advanced and retreated multiple times as global climate cooled and warmed repeatedly as Earth passed through and then gradually thawed out from the Little Ice Age.

Was the most recent retreat driven by human-caused global warming? For the most part certainly not, because most of the retreat since the Little Ice Age occurred long before before human-related carbon dioxide emissions reached a level where they conceivably could have been a factor. Achieving a proper perspective on the advance and retreat of alpine glaciers therefore requires data be viewed in the context of Holocene (last 10,000 years) glacial advance and retreat.

Barclay *et al.* (2009) have provided an extensive and up-to-date review of what is known about Alaskan Holocene glacial activity and its relationship to temperature. They found the "termini of land-based valley glaciers were in retracted positions during the early to middle Holocene," but "neoglaciation was underway in some areas by 4.5–4.0 ka and major advances of land-based termini occurred by 3.0 ka." Most dramatic, however, were the Little Ice Age (LIA) glacial advances, which culminated in two phases in the 1540s–1710s and 1810s–1880s, of which they state, "moraines of these middle and late LIA maxima are invariably the Holocene maxima in coastal southern Alaska," adding, "LIA advances are also recognized as major expansions in all glacierized mountain ranges in Alaska." In addition, they state researchers have determined "Holocene fluctuations of Alaskan land-terminating glaciers have primarily been forced by multi-decadal and longer timescale changes in temperature."

These observations suggest changes in glaciation in Alaska during the twentieth century likely started after the coldest portion of the Holocene, the Little Ice Age, when Earth cooled and then warmed again quite naturally, without any reference to rising human atmospheric CO_2 contributions.

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Other research

Similar inferences to those from drawn from Alaska have been drawn from other summaries of Holocene glacial history worldwide, including the following.

- Rodbell *et al.* (2009) reported on Andean glaciers in South America. These authors updated "the chronology of Andean glaciation during the Lateglacial and the Holocene from the numerous articles and reviews published over the past three decades," noting the Andes "offer an unparalleled opportunity to elucidate spatial and temporal patterns of glaciation along a continuous 68-degree meridional transect." They found "all presently glacierized mountain ranges contain multiple moraines deposited during the last 450 years" and "these correlate with the Little Ice Age as defined in the Northern Hemisphere." In addition, they note most Andean regions "reveal a nearly continuous temporal distribution of moraines during the Little Ice Age."

The occurrence of the Little Ice Age in essentially all of the glaciated portions of the Northern Hemisphere and the great meridional expanse of most of Andean South America, as well as the similar glacial activity of both parts of the planet during this time period, provide strong support for the proposition that montane glaciation began to retreat when much of the world commenced its return to its current, milder climatic state from what could be called the Holocene's "thermal basement," i.e., the Little Ice Age.

- In another study of Holocene glacier change, Nesje (2009) compiled, assessed, and evaluated "evidence of Late Glacial and Holocene glacier fluctuations in Scandinavia as deduced from ice-marginal features, marginal moraines, proglacial terrestrial and lacustrine sites, using especially new information that has become available since the review paper published by Karlen (1988)." Nesje reports data indicate significant late-glacial ice-sheet fluctuations and glacial contraction during the early and mid-Holocene and subsequent Neoglacial expansion, peaking during the Little Ice Age. These observations, he writes, are "in good agreement with other presently glaciated regions in the world," as described by Solomina *et al.* (2008) and references therein.
- Other authors have confirmed the Little Ice Age in Scandinavia, as in most parts of the world where glaciers formed and grew during that period, was a depressing and dangerous time (Luckman, 1994; Villalba, 1994; Smith *et al.*, 1995; Naftz *et al.*, 1996). Alpine glaciers advanced in virtually all mountainous regions of the globe during that period, eroding large areas of land and producing masses of debris. Ice streamed down mountain slopes to carve paths through the landscape, moving rocks and destroying all vegetation in their paths (Smith and Laroque, 1995).

Continental glaciers and sea ice expanded their ranges as well during this period (Grove, 1988; Crowley and North, 1991). Near Iceland and Greenland, in fact, the expansion of sea ice during the Little Ice Age was so great it isolated the Viking colony established in Greenland during the Medieval Warm Period, leading to its eventual abandonment (Bergthorsson, 1969; Dansgaard *et al.*, 1975; Pringle, 1997).

- Another Holocene study, this time of European glacial activity by Ivy-Ochs *et al.* (2009), presented "a summary of the evidence for suggested periods of glacier advance during the final phase of the Alpine Lateglacial and the Holocene," interweaving "data obtained from ^{10}Be surface exposure dating, radiocarbon dating of wood and peat washed out from the presently melting glacier tongues, dendrochronological investigations on wood from the glacierized basins, tree-line studies and archaeological evidence."

The authors found "the earliest Holocene (between 11.6 and about 10.5 ka) was still strongly affected by the cold climatic conditions of the Younger Dryas and the Preboreal oscillation," but "at or slightly before 10.5 ka rapid shrinkage of glaciers to a size smaller than their late 20th century size reflects markedly warmer and possibly also drier climate." After 3.3 ka, however, "climate conditions became generally colder and warm periods were brief and less frequent." Finally, they note "glaciers in the Alps attained their Little Ice Age maximum extents in the 14th, 17th and 19th centuries, with most reaching their greatest Little Ice Age extent in the final 1850/1860 AD advance."

Like their alpine glacier counterparts in Scandinavia, as described by Nesje (2009), glaciers of the European Alps also reached their maximum Holocene extensions close to the end of the Little Ice Age. At that time there existed the greatest potential for significant glacial retreat of the entire Holocene interglacial, for in an oscillatory climatic regime, the point of lowest temperature decline also represents the point of the greatest potential for a significant temperature increase. It would be expected, then, that the subsequent temperature recovery of Earth would be quite substantial, as there was much prior cooling to be overcome to return the planet to a climatic state more characteristic of the bulk of the Holocene.

- Considering glacial change over a shorter timeframe, Vincent *et al.* (2007) analyzed the impact of climate change over the past 100 years on high-elevation glaciated areas of the Mont Blanc range, including the ice fields that cover the Mont Blanc (4,808 m) and Dôme du Goûter (4,300 m) peaks. Surface ablation is negligible for these high-elevation areas, and the surface mass balance is mainly controlled by snow accumulation.

At Dôme du Goûter, ice fluxes were calculated through two transversal sections by two independent methods in order to assess long-term surface accumulation. A comparison between these results and recent accumulation observations, together with the strong relationship between valley precipitation and snow accumulation, suggests surface accumulation rates did not change significantly over the entire twentieth century. Vincent *et al.* state "the most striking features ... are the small thickness changes observed over the 20th century. For both areas, thickness variations do not exceed ±15 m. The average changes are +2.6 m at Dôme du Goûter and -0.3 m at Mont Blanc. Considering the uncertainty interval, i.e., ±5 m, it can be concluded that no significant thickness change is detectable over most of these areas." These findings show these high-elevation glaciated areas have not been significantly affected by climate change over the past 100 years.

- Kaser *et al.* (2010) examined the ice fields that top Mt. Kilimanjaro's highest peak, Kibo. Kaser *et al.* write these features have garnered "particular attention" since Irion (2001) attributed modern changes in them to "increased air temperature in the context of global warming" and Thompson *et al.* (2002) reported what they described as the "near extinction of the ice on Kibo," which they characterized as being "unprecedented over the last 11,700 years." Kaser *et al.* (2004) developed an alternative hypothesis, namely that atmospheric moisture controls the modern-time glacier changes on Kibo, as Kaser *et al.* (2010) indicate is also suggested by the work of Molg and Hardy (2004), Cullen *et al.* (2006, 2007), and Molg *et al.* (2003, 2006, 2009a, b). This finding, in their words, "rules out rising local air temperature (i.e. on the peak of Kibo) as the main driver of observed changes during the last 120 years."

Based on their review of all available information on present-day phenomena that control the glaciers on Kilimanjaro, Kaser *et al.* (2010) conclude "minor changes in thickness have no impact on the changing surface area of the tabular plateau glaciers," while noting "plateau glacier area decrease has been strikingly constant over the twentieth century" and "ablation rates of the ice walls are [also] persistently constant." In addition, their analyses suggest the mountain's plateau ice "may have come and gone repeatedly throughout the Holocene" and the reduction of plateau ice in modern times "is controlled by the absence of sustained regional wet periods rather than changes in local air temperature on the peak of Kilimanjaro."

Conclusions

Studies of Holocene glacial history show valley glaciers have waxed and waned worldwide for the past ten millennia. These glacial advances and retreats have occurred in sympathy with natural climate forcings. No evidence exists that unnatural glacial retreat occurred in the late twentieth century forced by human carbon dioxide emissions.

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5.9.2 European Alpine Glaciers

European alpine glaciers provide most of the longer historical and instrumented records of fluctuations in valley glacier size. Despite a large corpus of research literature, no paper yet demonstrates any correlation between increasing atmospheric CO_2 levels and the glacial melting projected by IPCC computer models, or supports their claim that Earth has recently warmed to its highest temperature of the past thousand years.

We summarize below recent studies of European glaciers, some of which have been stable or even advancing over the past 30 years despite the mild late twentieth century warming.

Joerin *et al.* (2006) used radiocarbon dating of materials found in subglacial and proglacial sediment, together with previously published data, to construct a Holocene glacial history of the Swiss Alps over the past ten thousand years. The results demonstrate "alpine glacier recessions occurred at least 12 times during the Holocene" and, glacier retreats have decreased in frequency since 7,000 years ago, and especially since 3,200 years ago, a trend that culminated in the Little Ice Age maximum advance. Moreover, the last major glacial retreat occurred between 1,400 and 1,200 years ago, a little before the Medieval Warm Period. A similar retreat occurred in the Great Aletsch Glacier between 1,200 and 800 years ago (Holzhauser *et al.*, 2005)

Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 to compute the yearly mass balances of the Swiss Silvretta, Rhone, Aletsch, and Gries glaciers. All four glaciers have steadily, if episodically, shrunk since 1865 (Figure 5.9.2.1), with no acceleration of the shrinkage over time, which is required by the anthropogenic global warming hypothesis.

Linderholm *et al.* (2007) examined the world's longest available mass-balance record from a mountain glacier, the Storglaciaren in northern Sweden. The record is well correlated with the records of other glaciers in the same region (Holmlund and Jansson, 1999), suggesting it is representative of northern Swedish glaciers. Figure

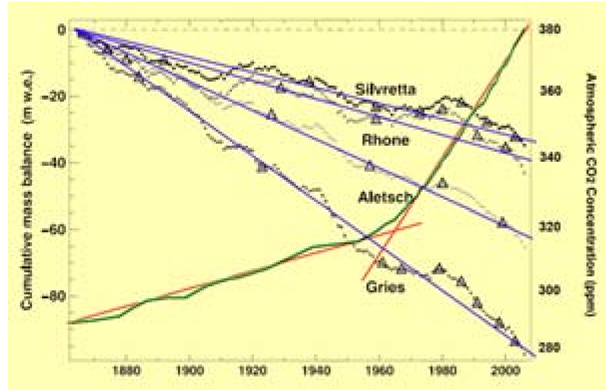

Figure 5.9.2.1. Huss *et al.* (2008) examined various ice and meteorological measurements made between 1865 and 2006 in the Swiss Alps to compute the yearly mass balances of four glaciers (linear trends fitted). Green line indicates atmospheric CO_2 concentrations, with two fitter linear segments (red lines). Adapted from Huss, M., Bauder, A., Funk, M., and Hock, R. 2008. Determination of the seasonal mass balance of four Alpine glaciers since 1865. *Journal of Geophysical Research* **113**: 10.1029/2007JF000803.

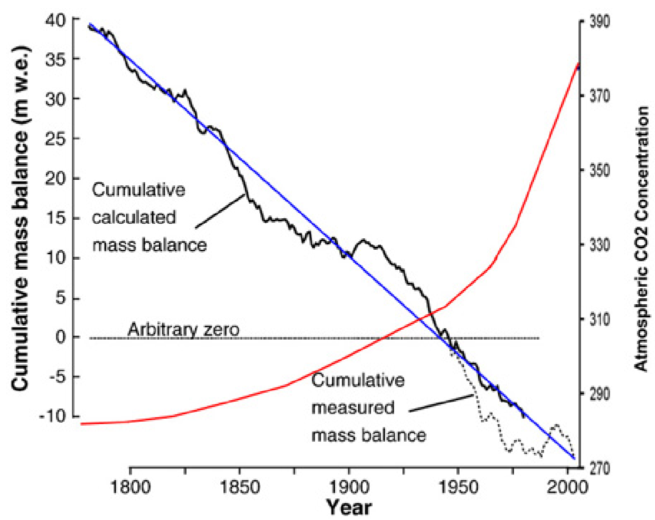

Figure 5.9.2.2. The cumulative reconstructed net mass balance history of Sweden's Storglaciaren, to which we have added the fit-by-eye descending linear relationship (blue line), and the history of the atmosphere's CO_2 concentration (red line). Adapted from Linderholm, H.W., Jansson, P., and Chen, D. 2007. A high-resolution reconstruction of Storglaciaren mass balance back to 1780/81 using tree-ring and circulation indices. *Quaternary Research* **67**: 12–20.

5.9.2.2 shows the Storglaciaren mass balance, plotted together with the record of atmospheric CO_2 over the same time period. It is evident the same pattern of progressive ice shrinkage seen in glaciers in the

European Alps occurs at Storglaciaren, and no acceleration of melting occurs during the time of strong CO_2 increase in the second half of the twentieth century.

D'Orefice *et al.* (2000) derived a post-Little Ice Age (LIA) history for the southernmost glacier of Europe, Ghiacciaio del Calderone. The surface area of this glacier underwent slow ice wastage from 1794 to 1884, after which a more rapid reduction in area continued to 1990, by which time the glacier had lost about half its LIA surface area.

Other European glaciers show a different pattern and have not experienced consistent, progressive loss of mass. For example, glaciers in the Central Swiss Alps experienced two periods of advance, around 1920 and 1980 (Hormes *et al.*, 2001). Braithwaite (2002) reported for the period 1980–1995 "Scandinavian glaciers [have been] growing, and glaciers in the Caucasus are close to equilibrium"; and Braithwaite and Zhang (2000) reported a significant upward trend in the mass balance of Sweden's Storglaciaren over the past 30–40 years. Additional evidence for post-LIA glacial expansion is provided by the Solheimajokull outlet glacier, southern coast of Iceland. Mackintosh *et al.* (2002) report a post-LIA minimum of 13.8 km length for this glacier in 1970, which thereafter expanded to 14.3 km by 1995. The minimum length of 13.8 km observed in 1970 also did not eclipse an earlier 300-year minimum length of 13.2 km which occurred in 1783.

Recent glacial advances also have occurred in Norway. Chinn *et al.* (2005) report glacial recession was most strongly expressed there in the middle of the twentieth century during the 1915 to 1945 warm period, ending during the late 1950s to early 1960s; then, after some years with more or less stationary glacier front positions, the glaciers began to advance during the 1945 to 1977 cool period, accelerating in the late 1980s. Around 2000, some of the glacial advance began to slow, though "most of the larger outlets with longer reaction times are continuing to advance." Chinn *et al.* report "the distances regained and the duration of this recent advance episode are both far greater than any previous readvance since the Little Ice Age maximum, making the recent resurgence a significant event." Much the same changes have occurred since 1988 "at all [western] maritime glaciers in both southern and northern Norway."

Conclusions

The studies summarized above show no European-wide correlation exists between increasing atmospheric CO_2 levels and simple glacial melting. Instead, European glaciers display an episodic history, with phases of both retreat and advance throughout the Holocene and over the past quarter-century. During the period over which the IPCC claims Earth has warmed to its highest temperature of the past thousand years, some glaciers advanced, others retreated, and others remained essentially stable.

The histories of glaciers such as the Storglaciaren, which display cumulative post-Little Ice Age retreats, provide no compelling evidence that the retreat had anything to do with the air's CO_2 content, not least because retreat commenced long before significant levels of industrial emissions had built up. As much to the point, a glacier like the Great Aletsch Glacier attained a length in AD 1000 only slightly less than its length today—despite there having been fully 100 ppm less CO_2 in the air then than there is today.

It is clear the ice-loss history of European glaciers was not influenced by the increase in the rate-of-rise of the air's CO_2 content that occurred between 1950 and 1970; their rate of shrinkage also was not materially increased by what the IPCC calls the unprecedented warming of the past few decades.

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5.9.3 Asia: Himalayan Glacier History

Concern about melting Himalayan glaciers has been led by the IPCC. Alarmist assertions have included claims that almost all Indian glaciers, including the Gangotri Glacier, will vanish from Earth in the next few decades, accompanied first by flooding and then by the drying of glacial-fed rivers, desertification, sea-level rise, submergence of coastal areas, spread of diseases, and a drop in the production of food grains—all, of course, as a result of anthropogenic global warming. Early in 2011 it was discovered the IPCC's key reference for such alarmist claims was an unrefereed report published by an environmentalist lobby group.

Meanwhile, Bali *et al.* (2011) carried out a comprehensive review of Himalayan glaciers, noting the Geological Survey of India has identified more than 9,000 valley glaciers in India and at least 2,000 more in Nepal and Bhutan (Raina, 2006), few of which are instrumented to modern standards. Hewitt (2010), investigating glaciers in the Karakoram, comments, "emerging evidence suggests that alarmist reports about the Himalaya are, at best, exaggerated," as also pointed out by Raina (2009) and Armstrong (2010). There is strong evidence for anomalous post-Little Ice Age glacier expansion in parts of the Karakoram, nourished not only by snowfall but also by avalanche contributions.

Hewitt (2005, 2011) found Karakoram glaciers have declined by only 5 percent or so since the early twentieth century, mainly between the 1920s and 1960s. Ice loss slowed in the 1970s (Mayewski and Jensche, 1979) during the 1945–1977 cool period, when some glaciers underwent modest advances (Kotlyakov, 1997), and modest retreat then prevailed again from the mid-1980s through the 1990s warm period. Most recently, "since the late 1990s we have reports of glaciers stabilizing and, in the high Karakoram, advancing (Hewitt, 2005; Immerzeel *et al.*, 2009)," while "total snow cover has been increasing in the high Karakoram (Naz *et al.*, 2009)."

Such a glacial history cannot have been driven simply by increasing anthropogenic carbon dioxide emissions, but rather must reflect the complex interaction of the several major processes that control glacier dynamics. In the high Himalaya, Hewitt points out, the extent and sustained high elevations of the main Karakoram, together with the "all-year accumulation regime, help to buffer glaciers against 'warming,'" should it start to occur again. He also notes "various investigations report cooler summers recently and greater summer cloudiness and snow cover (Fowler and Archer, 2006; Naz *et al.*, 2009; Scherler *et al.*, 2011), which potentially should lead to reduced average ablation rates or numbers of 'ablation days.'"

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Other research

Other evidence regarding the stability and natural variation of Himalayan glaciers, especially those in the western Karakoram Ranges, is further described and discussed in the following research papers.

- Schmidt and Nusser (2009) used a multitemporal/multiscale approach to studying glacial change in the Nanga Parbat region, Northern Pakistan, using historical data, repeat photography, and satellite imagery to develop a 70-year history of the behavior of that region's Raikot Glacier. They found only "relatively small rates of recession and surface changes over the last seven decades," noting "some well-defined large boulders remain in the same position in 2006 as in 1934," which indicates a high stability for the proglacial area and lateral moraines. In these respects, the Raikot Glacier is similar to "most debris-covered glaciers in the northwest Himalaya and in the nearby Karakoram, Hindu Kush and Kun Lun ranges, Raikot Glacier [which] show only minor retreating rates since the 1980s." Schmidt and Nusser report "glacier fluctuations over the past 70 years are characterized by retreat between the 1930s and 1950s, a marked advance between the 1950s and 1980s, and a relatively stable situation after 1992," but with no general trend of reducing ice mass since the 1930s.
- Chaujar (2009) used lichenometric dating of loop moraines on the Chorabari Glacier, Garhwal Himalayas to establish its history during and after the Little Ice Age. Noting his results are consistent with "research on various glaciers of the northern and southern hemisphere [which] has shown that most of them started their retreat in the mid-18th century, thereby indicating the end of the Little Ice Age maximum," he suggests this pattern of deglaciation may be a global phenomenon.
- Copland *et al.* (2011) used a combination of previously published literature and repeat satellite imagery to catalog ice behavior in the Karakoram since 1961. They found "there has been a marked increase in the recent occurrence of glacier surging in the Karakoram" associated with "a significant increase in winter, summer, and annual precipitation in the Karakoram over the period 1961–1999." In particular, there has been "a doubling in the number of new surges in the 14 years after 1990 (26 surges) than in the 14 years before 1990 (13 surges)." This increase in glacier surging correlates with the positive mass balances reported for the Karakoram by Gardelle *et al.* (2011) and others over the past few decades and is consistent with the many other glaciological indicators of recent ice stability or expansion in this area reported by Hewitt (2005), Pecci and Smiraglia (2000), Mayer *et al.* (2006), and Quincey *et al.* (2009).
- In their review of glacial activity in the Garhwal Himalaya, Bali *et al.* (2011) report the Gangotri Glacier, which was earlier receding at a rate of around 26 m/year between 1935 and 1971 (Raina, 2003; Sharma and Owen, 1996; Naithani *et al.*, 2001; Srivastava, 2003), has more recently shown a gradual decline in rate of recession, falling to 17 m/year for 1974–2004 and 12 m/year for 2004–2005 (Kumar *et al.*, 2008). The Dokriana Glacier maintained an overall constant rate of recession (around 16–18 m/year) between the years 1962 and 1995 (Dobhal *et al.*, 2004). The recession of the Pindari Glacier diminished from about 26 m/year for 1845–1906 to about 6.5 m/year in 1966–2007 (Bali *et al.*, 2009), and the Milam Glacier has exhibited a steady rate of recession of around 16.5 m/year over the past 150 years (Shukla and Siddiqui, 2001). The terminus of the Donagiri Glacier has exhibited intermittent recession and advance (Srivastava and Swaroop, 2001; Swaroop *et al.*, 2001), and the Satopanth Glacier, which earlier had been receding at the rate of 22.86 m/year, showed a recession rate of 6.5 m/year during 2005–2006 (Ganjoo and Koul, 2009). Most conspicuously, the 70-km-long Siachin glacier "has been standing steady for the last several decades," exhibiting an almost stable terminus that receded by only 8–10 m in 1995–2008 (Ganjoo and Koul, 2009)

and showing signs of advancement during the last decade (Sinha and Shah, 2008).

- Azam *et al.* (2012) describe recent glaciological changes in the western Himalaya using mass balance and surface ice flow velocity measurements made in 2002–2010 on the Chhota Shigri Glacier in the Pir Panjal Range, which they compare with similar data collected in 1987–1989. They find “the glacier has experienced a period of near-zero or slightly positive mass balance in the 1990s … [before] … starting to shrink at the beginning of the 21st century,” with only a small change in position of the terminus between 1988 and 2010.

Noting the Chhota Shigri seems to be representative of other glaciers in the Pir Panjal range (Berthier *et al.*, 2007), Azam *et al.* conclude many Western Himalayan glaciers may have experienced growth rather than shrinkage during the last 10–12 years of the twentieth century. The authors note “this result challenges the generally accepted idea that glaciers in the Western Himalaya have been shrinking rapidly for the last few decades” as, for example, implied by Solomon *et al.* (2012) in the IPCC’s *Fourth Assessment Report*.

- Hewitt (2005) noted the west end of the Himalayan arc, where China, India, and Pakistan meet, was characterized by a recent anomalous gain of mass by Karakoram glaciers. This feature was referred to in subsequent studies by Zemp *et al.* (2009), Cogley (2011), and Scherler *et al.* (2011), becoming known as the “Karakoram anomaly.”

Noting the paucity of data on the Karakoram, Gardelle *et al.* (2012) set out to calculate a regional mass balance for glaciers in the central Karakoram for 1999–2008 based on differences between two sets of digital elevation data, one from the February 2000 Shuttle Radar Topographic Mission (SRTM) and the other from the December 2008 optical stereo imagery acquired by the Satellite Pour l’Observation de la Terre (SPOT5) program. Gardelle *et al.* (2012) report the presence of “a highly heterogeneous spatial pattern of changes in glacier elevation, which shows that ice thinning and ablation at high rates can occur on debris-covered glacier tongues,” and which results in “the regional mass balance [being] just positive at +0.11 ± 0.22 m/year water equivalent.” Glacier expansion or speed-up consistent with this result has been previously reported by Hewitt (2005), Quincey *et al.* (2009), and Heid and Kaab (2011).

- In other research, “more than 50% of Karakoram glaciers were advancing or stable between 2000 and 2008” (Scherler *et al.*, 2011), and Fuita and Nuimura (2011) reported a descending trend in the modeled equilibrium-line altitude in the Karakoram during 1976–1995. Fowler and Archer (2006) reported an increase in winter precipitation since 1961, a potential source for greater accumulation in the upper parts of glaciers (Hewitt, 2005; Quincey *et al.* 2009, 2011). Between 1961 and 2000, Fowler and Archer report, mean summer temperature declined at all climate stations in the region, probably resulting in a decreasing glacier melt.

Conclusions

In its *Fourth Assessment Report*, the IPCC wrote the likelihood of India’s western Himalayan glaciers “disappearing by the year 2035 or perhaps sooner is very high if the Earth keeps warming at the current rate” (Solomon *et al.*, 2007). Given the obvious importance of the Himalayan glaciers as water sources for the populous downstream lowlands of south Asia, this was an alarming scenario to promulgate, and Cogley *et al.* (2010) give an account of how this misinformation came to be adopted.

Shroder *et al.* (2000) had discovered an absence of rapid Himalayan melting some time before, during their fieldwork in 1993–1995, from which they state “the glacial fed rivers are thus not going to die an immediate death.” They pointed out “even if a time comes that there are no glaciers around, the rivers will still flow” because at the foothills the contribution of glacial melt water is only 10 to 15 percent of the total, the rest being supplied by rain and ground water.

Real-world empirical data are needed to test alarmist speculations about the disappearance of Himalayan glaciers. Byers (2007), Zemp and Haeberli (2007), and Kumar *et al.* (2008) all point out the Himalayan glacier response to climate change is poorly known, mainly because of the lack of long-term and continuous records of glacial fluctuations at sites throughout the mountain chain.

The research studies summarized above are beginning to provide the factual data required to improve our understanding of how Himalayan glaciers might respond to climate change. The beliefs of Solomon *et al.* (2007) are now more open to observational testing, and we no longer have to rely on speculative computer modeling projections.

Two main lines of empirical argument bear on the issue. The first, after Chaujar (2009), is based upon viewing twentieth century glacial change in the context of the post-LIA climatic warming that started in the 1860s and caused glacier shrinkages around the world, including in the Himalayas. As Chaujar notes, these changes started “long before the historical increase in the air's CO_2 content could have been involved in the process of their retreat." Hence, there is no reason to believe the late twentieth century warming, and glacial shrinkage where it occurred, were anything more than a continuation of the nonanthropogenic return of Earth from the frigid depths of the Little Ice Age.

The second argument is based on the growing number of local and regional studies becoming available from throughout the Himalayas. Though variability in ice-mass change exists from place to place, most recent studies have found the glaciers of the Indian subcontinent "are receding at a much slower pace in comparison to what they were about a few decades back" (Bali *et al.*, 2011; see also Yadav, *et al.,* 2004), or even growing in places in the Karakoram, Hindu Kush, and Western Himalayan ranges. This glacial growth appears to be driven "by a quirk of the atmospheric general circulation that is not understood"; "more snow is being delivered to the mountain range at present, and less heat" (Cogley, 2012). Gardelle *et al.* (2012) have provided strong evidence for the existence of an increasing ice mass balance in the Karakoram region, and Copland *et al.* (2011) stress that contrary to what is often claimed about many of Earth's mountain glaciers, "it is evident that glacier surging is more extensive than previously reported in the Karakoram and that the number of glacier surges has increased recently," driven by positive mass balances.

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5.9.4 African Glaciers

African montane glaciers are unusual in their close proximity to the equator, where ice can be maintained only at considerable heights; i.e. on large mountains. One of these, Kenya's Mt. Kilimanjaro, has achieved iconic status because of Ernest Hemingway's famous short story "The Snows of Kilimanjaro."

During the 1980s and 1990s, U.S. politicians Al Gore, John McCain, and Hilary Clinton, together with other public figures around the world, made emotional statements in support of reducing human-related CO_2, based on their (incorrect) understanding that Kilimanjaro's summit ice field was melting under the influence of anthropogenic global warming. Acknowledging subsequent research, Justice Michael Burton in his 2007 U.K. High Court judgement against Mr. Gore's film, *An Inconvenient Truth,* concluded such views are in error. Modern glacier recession on Kilimanjaro began around 1880, which rules out post-1950 human emissions as the primary cause, despite that belief being encouraged by scattered scientific reports (Alverson *et al.*, 2001; Irion, 2001; Thompson *et al.*, 2002). This oversimplified view is wrong, as shown in the following papers.

- Molg *et al.* (2003a) note all three glacier-bearing volcanic mountains in East Africa—Kilimanjaro (Tanzania, Kenya), Mount Kenya (Kenya), and Rwenzori (Zaire, Uganda)—have experienced strong ice field recession over the past century or so. They also report, after Hastenrath (2001), "there is no evidence of a sudden change in temperature [in East Africa] at the end of the 19th century," as confirmed by King'uyu *et al.* (2000) and Hay *et al.* (2002), who show East African twentieth century temperature records show diverse trends and do not exhibit a uniform warming signal.

- Georges and Kaser (2002) report on an automatic weather station installed in 2002 on a horizontal glacier surface at the Kilimanjaro Northern Icefield. Since then, monthly mean air temperatures have varied only slightly around the annual mean of -7.1°C, and air temperatures have never risen above freezing. It is difficult to understand how ice could melt under such conditions.
- Molg and Hardy (2004) used data from this weather station to derive an energy balance for the Kibo summit icefield on Mt. Kilimanjaro. They discovered "the main energy exchange at the glacier-atmosphere interface results from the terms accounting for net radiation, governed by the variation in net shortwave radiation," which is controlled by surface albedo (and thus precipitation variability), which determines the reflective characteristics of the glacier's surface. Much less significant, according to the two researchers, is the temperature-driven turbulent exchange of sensible heat, which they say "remains considerably smaller and of little importance." Molg and Hardy conclude "modern glacier retreat on Kilimanjaro and in East Africa in general [was] initiated by a drastic reduction in precipitation at the end of the 19th century (Hastenrath, 1984, 2001; Kaser *et al.*, 2004)," and reduced accumulation and increased ablation have "maintained the retreat until the present (Molg *et al.*, 2003a)."
- Molg *et al.* (2003b) applied a radiation model to an idealized representation of the 1880 icecap of Kilimanjaro, concluding "modern glacier retreat on Kilimanjaro is much more complex than simply attributable to 'global warming only.'" Instead, and as reported by many other authors, the ice retreat has been "a process driven by a complex combination of changes in several different climatic parameters [e.g., Kruss, 1983; Kruss and Hastenrath, 1987; Hastenrath and Kruss, 1992; Kaser and Georges, 1997; Wagnon *et al.*, 2001; Kaser and Osmaston, 2002; Francou *et al.*, 2003; Molg *et al.*, 2003b], with humidity-related variables dominating this combination."
- Cullen *et al.* (2006) report "all ice bodies on Kilimanjaro have retreated drastically between 1912–2003," but they add the highest glacial recession rates on Kilimanjaro "occurred in the first part of the twentieth century, with the most recent retreat rates (1989–2003) smaller than in any other interval." In addition, they say no temperature trends over the period 1948–2005 have been observed at the approximate height of the Kilimanjaro glaciers, but there has been a small decrease in the region's specific humidity over this period.

In terms of why glacier retreat on Kilimanjaro was so dramatic over the twentieth century, the six researchers note for the mountain's plateau glaciers, there is no alternative for them "other than to continuously retreat once their vertical margins are exposed to solar radiation," which appears to have happened sometime in the latter part of the nineteenth century. They also report the "vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in 20th century climate have not altered their continuous demise." Consequently, the twentieth century retreat of Kilimanjaro's plateau glaciers is a long-term response to what we could call "relict climate change" that likely occurred in the late nineteenth century.

In the case of the mountain's slope glaciers, Cullen *et al.* say their rapid recession in the first part of the twentieth century shows they "were drastically out of equilibrium," which they take as evidence the glaciers "were responding to a large prior shift in climate." In addition, they report "no footprint of multidecadal changes in areal extent of slope glaciers to fluctuations in twentieth century climate is observed, but their ongoing demise does suggest they are still out of equilibrium," and in this regard they add their continuing but decelerating demise could be helped along by the continuous slow decline in the air's specific humidity. Cullen *et al.* confidently conclude the glaciers of Kilimanjaro "are merely remnants of a past climate rather than sensitive indicators of 20th century climate change."

- Two additional studies, by Mote and Kaser (2007) and Duane *et al.* (2008), reject the temperature-induced decline hypothesis for Kilimanjaro. Duane *et al.* conclude "the reasons for the rapid decline in Kilimanjaro's glaciers are not primarily due to increased air temperatures, but a lack of precipitation," and Mote and Kaser report "warming fails spectacularly to explain the behavior of the glaciers and plateau ice on Africa's Kilimanjaro massif ... and to a lesser extent other tropical glaciers."
- What, then, caused the ice fields of Kilimanjaro to recede steadily for so many years? Citing

"historical accounts of lake levels (Hastenrath, 1984; Nicholson and Yin, 2001), wind and current observations in the Indian Ocean and their relationship to East African rainfall (Hastenrath, 2001), water balance models of lakes (Nicholson and Yin, 2001), and paleolimnological data (Verschuren *et al.*, 2000)," Molg *et al.* (2003a, b) say "all data indicate that modern East African climate experienced an abrupt and marked drop in air humidity around 1880," and the resultant "strong reduction in precipitation at the end of the 19th century is the main reason for modern glacier recession in East Africa," as it considerably reduces glacier mass balance accumulation, as demonstrated for the region by Kruss (1983) and Hastenrath (1984). In addition, they note "increased incoming shortwave radiation due to decreases in cloudiness—both effects of the drier climatic conditions—plays a decisive role for glacier retreat by increasing ablation, as demonstrated for Mount Kenya and Rwenzori (Kruss and Hastenrath, 1987; Molg *et al.*, 2003a)."

- Kaser *et al.* (2004) conclude all relevant "observations and facts" clearly indicate "climatological processes other than air temperature control the ice recession in a direct manner" on Kilimanjaro, and "positive air temperatures have not contributed to the recession process on the summit." Those conclusions directly contradict Irion (2002) and Thompson *et al.* (2002), who see the recession of Kilimanjaro's glaciers as a direct consequence solely of increased air temperature.

Conclusions

In support of the findings of Molg *et al.* (2003a, b), for Africa, analyses of glacier retreat throughout the tropics uniformly suggest that changes in air humidity have been dominant in controlling modern retreat where it has occurred [e.g., Kaser and Georges (1997) for the Peruvian Cordillera Blanca and Francou *et al.* (2003) for the Bolivian Cordillera Real (both South American Andes); Kruss (1983), Kruss and Hastenrath (1987), and Hastenrath (1995) for Mount Kenya (East Africa); and Molg *et al.* (2003a) for the Rwenzori massif (East Africa)].

Kaser *et al.* (2004) conclude "changes in air humidity and atmospheric moisture content (e.g. Soden and Schroeder, 2000) seem to play an underestimated key role in tropical high-mountain climate (Broecker, 1997)." Regarding East African montane glaciers, it is important to remember "the dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser and Noggler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Molg *et al.*, 2003b)." These factors are related to a drying of the regional atmosphere that commenced around 1880 and lasted through the twentieth century.

We conclude warming air temperatures have not been the dominant cause of recent ice recession on tropical mountain glaciers, Kilimanjaro included.

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5.9.5 South America

Studies of alpine glaciers from South America fail to provide evidence for widespread or uniform glacial retreat under the influence of modern global warming.

- Harrison and Winchester (2000) used dendrochronology, lichenometry, and aerial photography to date nineteenth and twentieth century fluctuations of the Arco, Colonia, and Arenales glaciers on the eastern side of the Hielo Patagonico Norte in southern Chile. These glaciers, together with four others on the western side of the ice field, began to retreat from their Little Ice Age maximum positions between 1850 and 1880. The trend of retreat continued "through the first half of the 20th century with various still-stands and oscillations between 1925 and 1960 ... with retreat increasing since the 1960s," as also has been observed at many Northern Hemisphere sites.
- Glasser *et al.* (2004) describe glacial fluctuations in the two major ice fields of Patagonia: the Hielo Patagonico Norte and the Hielo Patagonico Sur. The evidence indicates glacial advance and retreat since about 6,000 ^{14}C years BP in concert with the known Roman Warm Period, cold Dark Ages, warm Medieval Warm Period, cold Little Ice Age and twentieth century warming. A similar pattern of glacial activity occurred to the east of the Hielo Patagonico Sur, in the Rio Guanaco region of the Precordillera. Here, Wenzens (1999) detected five distinct periods of glacial advancement: "4500–4200, 3600–3300, 2300–2000, 1300–1000 ^{14}C years BP and AD 1600–1850." The glacial advancements during

the cold interval prior to the Roman Warm Period constitute "part of a body of evidence for global climatic change around this time (e.g., Grosjean *et al.*, 1998; Wasson and Claussen, 2002). This period coincided with the abrupt decrease in solar activity that led van Geel *et al.* (2000) to stress the importance of solar irradiance as a driver for climate variation.

Glacial histories similar to those of Patagonia have been described from geomorphological moraine analysis recorded from other parts of southern Chile (e.g., Kuylenstierna *et al.*, 1996; Koch and Kilian, 2001), the Peruvian Cordillera Blanca (Kaser and Georges, 1997), and the Bolivian Cordillera Real (Francou *et al.*, 2003). Further afield, similar histories are also known from areas peripheral to the North Atlantic and in central Asia (cf. Grove, 1988; Savoskul, 1997).

- Georges (2004) constructed a twentieth century history of glacial fluctuations in the Cordillera Blanca of Peru, the largest glaciated area in the tropics. Glacier recession of unknown extent occurred early in the century, followed by a marked readvance in the 1920s that nearly reached the Little Ice Age maximum. Thereafter came a very strong glacial mass shrinkage in the 1930s–1940s, quiescence, and an intermediate retreat from the mid-1970s until the end of the century. Georges comments, "the intensity of the 1930s–1940s retreat was more pronounced than that of the one at the end of the century," the data indicating the rate of wastage in the 1930s–1940s was twice as great as that of the last two decades of the twentieth century. The advances in the Cordillera Blanca in the late 1920s were almost as great as those experienced there during the Little Ice Age.
- Koch and Kilian (2005) used dendrochronology to map and date the moraine systems of Glaciar Lengua and neighboring glaciers of Gran Campo Nevado in the southernmost Andes of Chile. They found the culmination of the Little Ice Age glacial advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Rothlisberger, 1986; Aniya, 1996), but glaciers at Hielo Patagonico Norte and Hielo Patagonico Sur also formed prominent moraines around 1870 and 1880 (Warren and Sugden, 1993; Winchester *et al.*, 2001; Luckman and Villalba, 2001).
- Polissar *et al.* (2006) used two 1,500-yr-long sediment cores from Lakes Mucubaji and Blanca, Venezuela, to reconstruct proxy records for glacier activity, temperature, and moisture balance in that part of the tropical Andes (the Cordillera de Merida). Techniques used included measurement for biogenic silica, magnetic susceptibility, total organic carbon (TOC), total nitrogen (TN), δ^{13}CTOC, δ^{15}NTN, and C/N.

Polissar *et al.* note the peaks and troughs in the susceptibility records match fluctuations of solar irradiance reconstructed from ^{10}Be and δ^{14}C measurements; spectral analysis identifies significant peaks at 227 and 125 years in both the irradiance and magnetic susceptibility records, which match the de Vries and Gleissberg oscillations known from solar irradiance reconstructions; and the magnetic susceptibility record follows the solar-irradiance reconstruction during 1520–1650 but is not correlated with solar and volcanic forcings during that time. The four glacial advances that occurred between AD 1250 and 1810 coincide with solar-activity minima and also with temperature declines of -3.2 ± 1.4°C and precipitation increases of ~+20%.

Conclusions

These South American studies make clear the strong correlation between glacial advance and retreat and the warmings and coolings of the past several centuries. Moreover, independent evidence for solar control, including at the shorter de Vries (~208 yr) and Gleissberg (~80 yr) wavelengths, is provided by Polissar *et al.*'s work in Venezuela.

Most of the observed glacial cycles date from long before a time when human CO_2 emissions could have been a cause. In addition, CO_2 levels lower than those of the twentieth century occurred during older warm intervals, and no unusual glacial retreats occurred during the mild twentieth century warming.

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5.9.6 North America

The history of North American glacial activity fails to support the claim that anthropogenic CO_2 emissions are causing glaciers to melt. Relevant studies include the following.

- Dowdeswell *et al.* (1997) analyzed the mass balance histories of the 18 Arctic glaciers with the longest observational records, finding that just over 80 percent of them displayed negative mass balances over the last half of the twentieth century. However, they note "ice-core records from the Canadian High Arctic islands indicate that the generally negative glacier mass balances observed over the past 50 years have probably been typical of Arctic glaciers since the end of the Little Ice Age." They conclude "there is no compelling indication of increasingly negative balance conditions which might, a priori, be expected from anthropogenically induced global warming."
- Calkin *et al.* (2001) reviewed current research on Holocene neoglaciations along the Gulf of Alaska between the Kenai Peninsula and Yakutat Bay, where several periods of glacial advance and retreat have occurred during the past 7,000 years. Over the younger part of this record, a general glacial retreat occurred during the Medieval Warm Period prior to AD 1200, after which three major advances occurred during the Little Ice Age: in the early fifteenth century, the middle seventeenth century, and the last half of the nineteenth century. During these three cold intervals, glacier equilibrium line altitudes were depressed from 150 to 200 m below present values as Alaskan glaciers also "reached their Holocene maximum extensions."
- Clague *et al.* (2004) documented glacier and vegetation changes at high elevations in the upper Bowser River basin in the northern Coast Mountains of British Columbia, based on studies of the distributions of glacial moraines and trimlines, tree-ring data, cores from two small lakes sampled for a variety of analyses (magnetic susceptibility, pollen,

diatoms, chironomids, carbon and nitrogen content, ^{210}Pb, ^{137}Cs, ^{14}C), similar analyses of materials obtained from pits and cores from a nearby fen, and by accelerator mass spectrometry radiocarbon dating of plant fossils, including wood fragments, tree bark, twigs, and conifer needles and cones.

These data provided copious evidence for the occurrence of a glacial advance that began about 3,000 years ago and probably lasted for several hundred years—equivalent to the unnamed cold period prior to the Roman Warm Period that is also known from South America. Evidence also was present for a second phase of glacial activity beginning about 1,300 years ago and which could equate with the Dark Ages Cold Period. A third, and the most extensive and recent, neoglacial interval began shortly after the Medieval Warm Period at about AD 1200 and ended in the late 1800s. Clague *et al.* comment "glaciers achieved their greatest extent of the past 3,000 years and probably the last 10,000 years" during this Little Ice Age period.

- Wiles *et al.* (2004) derived a composite Glacier Expansion Index (GEI) for Alaska based on "dendrochronologically derived calendar dates from forests overrun by advancing ice and age estimates of moraines using tree-rings and lichens" for three climatically distinct regions—the Arctic Brooks Range, the southern transitional interior straddled by the Wrangell and St. Elias mountain ranges, and the Kenai, Chugach, and St. Elias coastal ranges—after which they compared this history of glacial activity with "the ^{14}C record preserved in tree rings corrected for marine and terrestrial reservoir effects as a proxy for solar variability" and with the history of the Pacific Decadal Oscillation (PDO) derived by Cook (2002).

Wiles *et al.* discovered "Alaska shows ice expansions approximately every 200 years, compatible with a solar mode of variability," specifically, the de Vries 208-year solar cycle; by merging this cycle with the cyclical behavior of the PDO, they obtained a dual-parameter forcing function even better correlated with the Alaskan composite GEI, with major glacial advances clearly associated with the Sporer, Maunder, and Dalton solar minima.

Wiles *et al.* said "increased understanding of solar variability and its climatic impacts is critical for separating anthropogenic from natural forcing and for predicting anticipated temperature change for future centuries." They made no mention of possible CO_2-induced global warming in discussing their results. Alaskan glacial activity, which in their words "has been shown to be primarily a record of summer temperature change (Barclay *et al.*, 1999)," appears to be sufficiently well described within the context of centennial (solar) and decadal (PDO) variability superimposed upon the millennial-scale (non-CO_2-forced) variability that produces longer-lasting Medieval Warm Period and Little Ice Age conditions.

- Pederson *et al.* (2004) used tree-ring reconstructions of North Pacific surface temperature anomalies and summer drought as proxies for winter glacial accumulation and summer ablation, respectively, to create a 300-year history of regional glacial Mass Balance Potential (MBP), which they compared with historic retreats and advances of Glacier Park's extensively studied Jackson and Agassiz glaciers in northwest Montana.

As they describe it, "the maximum glacial advance of the Little Ice Age coincides with a sustained period of positive MBP that began in the mid-1770s and was interrupted by only one brief ablation phase (~1790s) prior to the 1830s," after which they report "the mid-19th century retreat of the Jackson and Agassiz glaciers then coincides with a period marked by strong negative MBP." From about 1850 onward, they note "Carrara and McGimsey (1981) indicate a modest retreat (~3-14 m/yr) for both glaciers until approximately 1917." At that point, they report, "the MBP shifts to an extreme negative phase that persists for ~25 yr," during which period the glaciers retreated "at rates of greater than 100 m/yr."

Continuing with their history, Pederson *et al.* report "from the mid-1940s through the 1970s retreat rates slowed substantially, and several modest advances were documented as the North Pacific transitioned to a cool phase [and] relatively mild summer conditions also prevailed." From the late 1970s through the 1990s, they say, "instrumental records indicate a shift in the PDO back to warmer conditions resulting in continuous, moderate retreat of the Jackson and Agassiz glaciers."

- Easterbrook (2010, 2011) described Holocene glacial advances and retreats on Mt. Baker in the North Cascade Range (Washington) that correlate well with the climate changes documented in the Greenland GISP2 ice core and the global temperature curve. Ice margins of Mt. Baker glaciers are shown on air photos dating back to 1943 (see Figure 5.9.6.1) (Easterbrook, 2010, 2011; Harper, 1993). Glaciers that had been retreating since at least the 1920s advanced during the 1947–1977 cool period to positions down-valley from their 1943 termini. They began to retreat once again at the start of the 1977–2007 warm period, and recent termini of the Easton and Boulder glaciers are about 450 m up-valley from

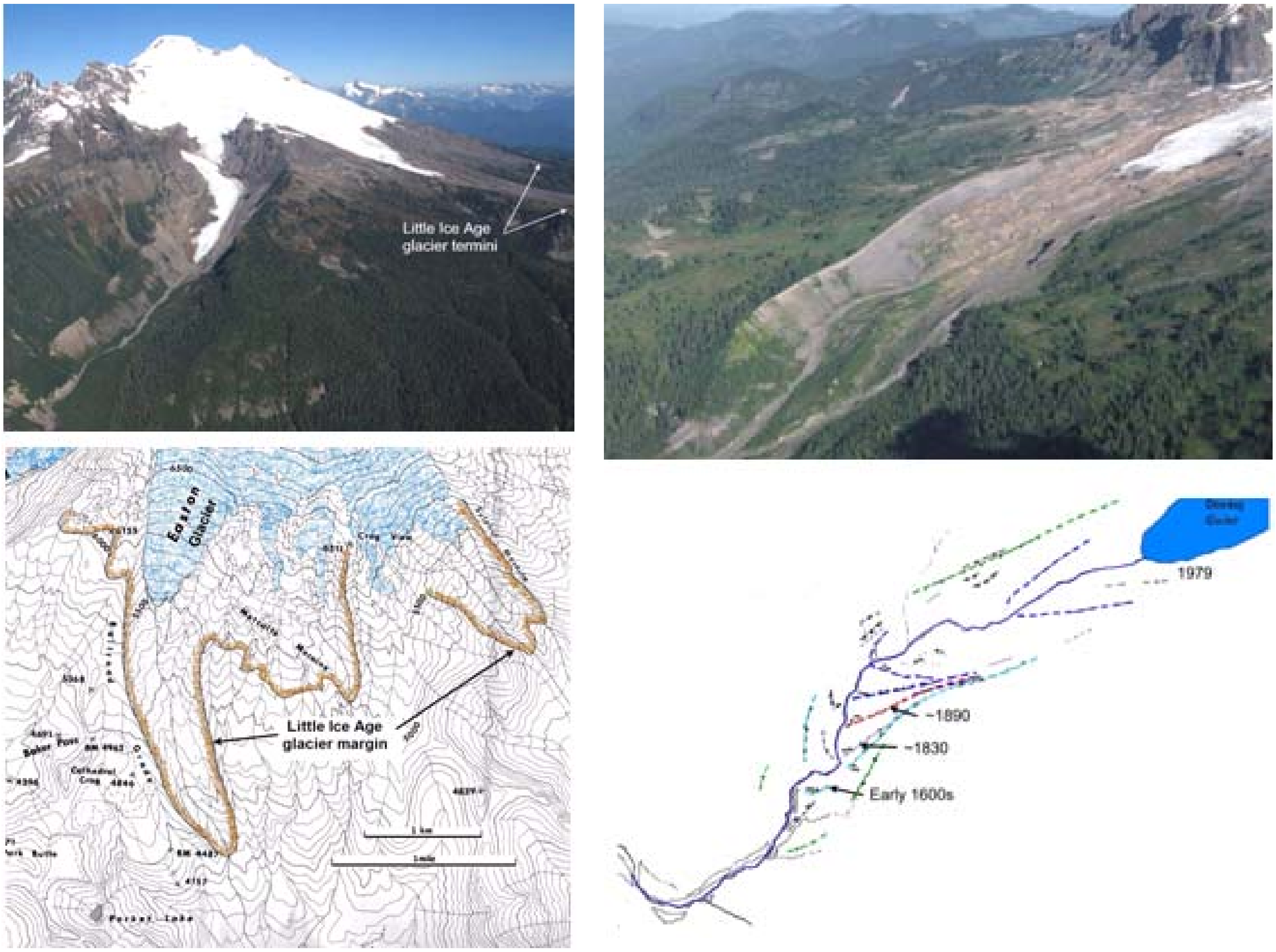

Figure 5.9.6.1. LEFT COLUMN: Photo (upper) and topographic map (lower) of ice retreat from the Little Ice Age maximum, Deming and Easton glaciers, Mt. Baker Washington. RIGHT COLUMN: Photo (upper) and sketch map (lower) of dated moraines down-valley from the Deming glacier on Mt. Baker, Washington. All adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future*. Elsevier, pp. 3–51.

their 1979 positions. These glacial fluctuations closely follow the global temperature record and indicate the warming and cooling cycles seen in the glacial record mimic global climate change. Thus, prehistoric glacial fluctuations also record global climate change.

The glaciers on Mt. Baker show a regular pattern of advance and retreat that matches sea surface temperatures in the nearby northeast Pacific Ocean (the Pacific Decadal Oscillation) (Figure 5.9.6.2), showing the glacier fluctuations occur in parallel with changes in sea surface temperature. Because the glacial record extends back many centuries, it can be used as a proxy for climate change (Figure 5.9.6.3).

- Munroe *et al.* (2012) provide a lacustrine-based Neoglacial record for the glaciers of Montana's Glacier National Park (GNP), where a reduction in the area of glaciers in excess of 36 percent since approximately 1850 has been reported (Key *et al.*, 2002). Munroe *et al.* used analyses of the sedimentary cores for properties sensitive to the extent and activity of upstream glacier ice, including water, organic matter, carbonate, and biogenic silica content; bulk density; mass accumulation rate; phosphorus fractionation; magnetic susceptibility; L*a*b* color values; and grain size distributions.

Munroe *et al.* report all but one of their records contain evidence for glacier advances during the last millennium, corresponding with the Little Ice Age, which they describe as "the most extensive event" of the entire Neoglacial and is "strongly expressed globally—Davis *et al.* (2009)." They found the Little

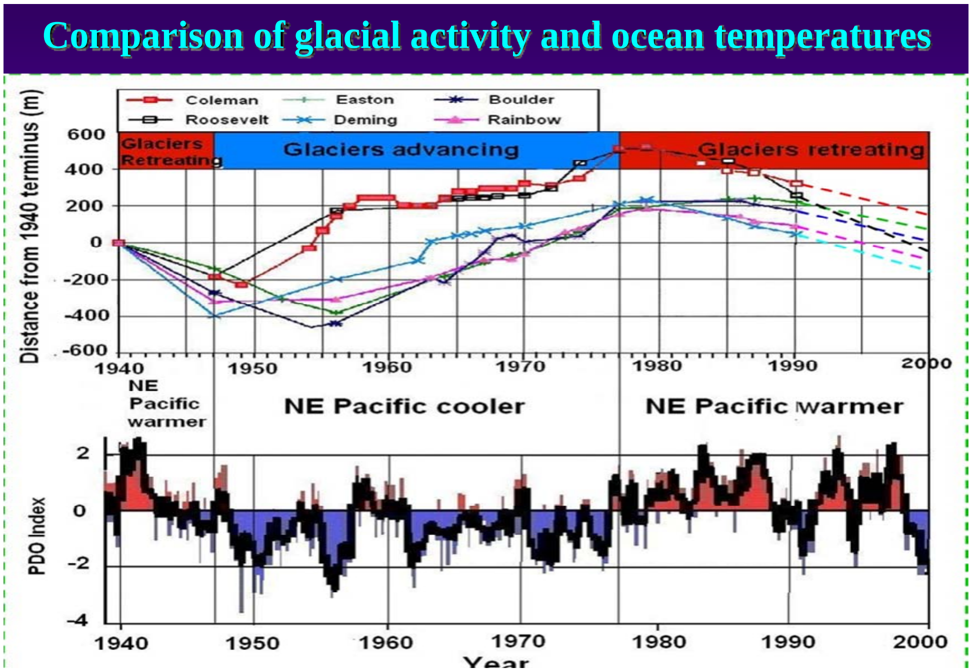

Figure 5.9.6.2. Comparison of advance and retreat of glaciers on Mt. Baker, Washington, with the Pacific Decadal Oscillation. Adapted from Easterbrook, D.J. 2011. *Geologic evidence of recurring climate cycles and their implications for the cause of global climate changes—the past is the key to the future*. Elsevier, pp. 3–51.

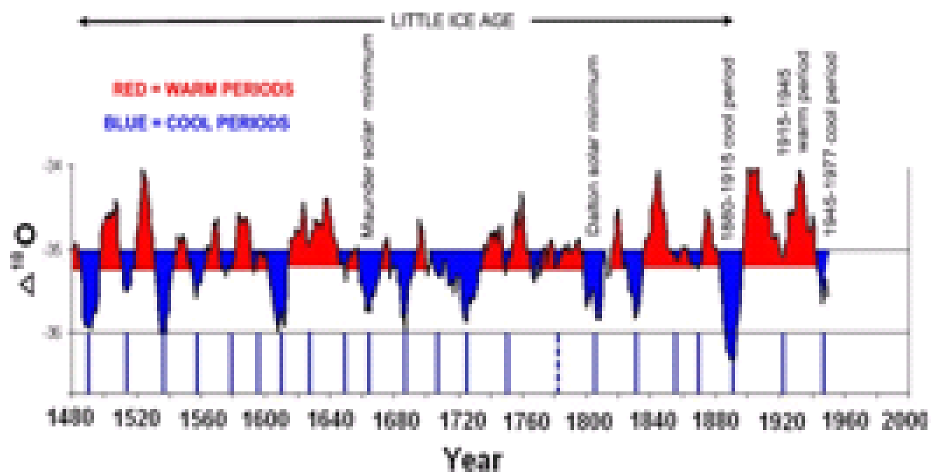

Figure 5.9.6.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460, based on data from Grootes and Stuiver, 1997). Also adapted from Easterbrook (2011).

Ice Age maximum advance was but the most recent in a series of advance/retreat cycles during the past several millennia, and its retreat "was the most dramatic episode of ice retreat in at least the last 1000 years."

Some scientists argue, despite the fact human emissions did not reach significant levels until one-hundred years later, that the end of the Little Ice Age in the late nineteenth century was caused by CO_2-induced global warming. Munroe *et al.* are not among this group. Instead, they contend both the birth and the death of the Little Ice Age were promoted by changes in solar irradiance, a conclusion supported by many other authors (Denton and Karlen, 1973; Bond *et al.*, 2001; Koch *et al.*, 2007). The quasi-periodic cycle of ~1,500 years that is involved also has been connected to glacier fluctuations in Europe (Holzhauser *et al.*, 2005; Matthews *et al.*, 2005;

Nussbaumer *et al.*, 2011). If these scientists are right about solar influences, then atmospheric CO_2 variability (which remained constant during several 1,500-year cycles during the Holocene) is likely to have played no significant role in recent temperature changes.

Conclusions

The history of North American montane glaciers demonstrates the occurrence of repeated cool/warm cycles, well before any possible influence by human-emitted CO_2. In terms of the currently observed climatic pattern driven by the PDO, glaciers are behaving precisely as they have in the past; i.e. are starting a new, cooler 25- to 30-year cycle. Extending this record into the future provides an opportunity to predict coming climate changes.

These findings stand in stark contrast to the IPCC-endorsed "hockey stick" temperature history of Mann *et al.* (1998, 1999), which neither matches the known history of glacial change nor portrays any Northern Hemispheric warming until around 1910.

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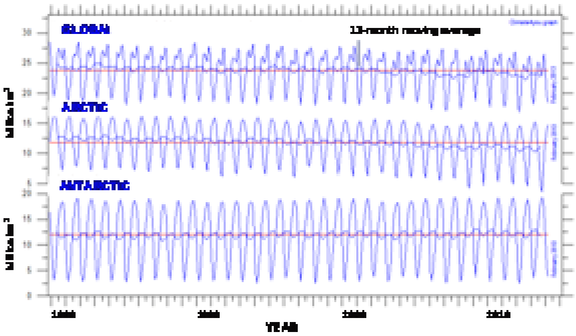

Figure 5.10.1. Arctic, Antarctic, and global sea ice area, 1979–2012 plotted using data from U.S. National Snow and Ice Data Center. Humlum, O. 2013. Sea ice extension in a longer time frame. Climate4You [Web site], http://www.climate4you.com/SeaIce.htm.

5.10 Sea and Lake Ice

Claims are commonly made that CO_2-induced global warming is melting sea ice in the Arctic, and potentially the Antarctic, and that such melting will accelerate as time passes.

Though semi-permanent sea ice exists today around the North Pole, fringing sea ice in both the Arctic and Antarctic is an annual, seasonal feature. Fringing sea ice is therefore particularly susceptible to fast advance or retreat depending upon local oceanographic and atmospheric changes. Quite major sea-ice changes are not uncommon and are not necessarily a result of climatic change; often, pulses of warm ocean water or atypical wind motions play a significant role.

Sea-ice expansion is driven by the spontaneous freezing of sea water in winter in areas of open polar ocean. Then, during the spring and summer months, and as daily solar radiation increases with higher Sun angle and longer day length, the sea ice melts and its area contracts. This annual cycle results in changes in area of sea ice of about 10 million km^2 each year in the Arctic and about 12 million km^2 in the Antarctic (see Figure 5.10.1).

The annual areal extent of sea ice is influenced by both ocean and atmospheric temperature, and in general the colder the winter the more sea ice that will form. The melting and break-up of sea ice is, however, more complex, in that winds and ocean currents often play a major role in breaking up, dispersing, and diminishing the area of sea ice, as was the case in the extensive diminution of ice in the Arctic Ocean in 2007 and 2012.

The freezing and melting of both land ice and sea ice is not just a simple function of temperature, but reflects complex changes in a number of environmental variables. The satellite observational record of sea ice spans only 1979–2012, and it has recently shown increases in ice area around Antarctica and decreases in area in the Arctic Ocean. There has been little net change in the overall global area of ice over the past 33 years, as shown in Figure 5.10.1. But 33 years is far too short a period of record from which to draw any meaningful conclusions about climate change.

Longer historical records demonstrate the area of Arctic ice has fluctuated in a multidecadal way in broad sympathy with past cycles in temperature, including shrinking to an area similar to that of recent years during periods of relative warmth in the 1780s and 1940s (see Figure 5.10.2) (Frauenfeld *et al.*, 2011). Earlier still, about 8,000 years ago during the early Holocene Climatic Optimum, geological records show temperatures up to 2.5^{O} C warmer than today resulted in strong Arctic glacier melt and therefore probably an almost or completely ice-free Arctic Ocean (e.g., Fisher *et al.*, 2006).

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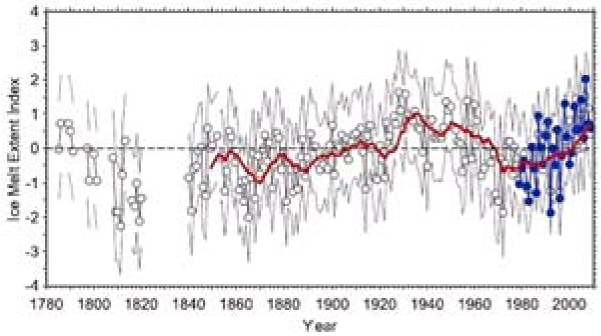

Figure 5.10.2. Estimated area of Arctic sea ice, 1780–2010. Adapted from Frauenfeld, O.W., Knappenberger, P.C., and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784-2009. *Journal of Geophysical Research* **116**: doi:10.1029/2010JD014918.

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5.10.1 Arctic Sea Ice

Arctic climate is complex and varies on a number of timescales with multiple causes (Venegas and Mysak, 2000). Identifying changes in Arctic sea ice that can be attributed to an increase in temperature caused by the burning of fossil fuels has proved difficult. The task is further complicated because most of the records used in the debate comprise only a few years to a few decades of data, and they yield different trends depending on the data set or period of time studied.

The dynamic, rather than climatic, aspect of sea-ice change is well exemplified in a recent satellite study by Scott and Marshall (2010), who aimed to resolve a dilemma: Whereas there has been a trend toward earlier summer breakup of sea ice in western Hudson Bay, Canada, which some authors (Stirling *et al.*, 1999; Gagnon and Gough, 2005) have attributed to long-term warming in the region, Dyck *et al.* (2007) report no regional warming trend has elapsed sufficient to have caused this change.

Scott and Marshall combined passive microwave data collected by the Nimbus 7 satellite and Defense Meteorological Satellite Program satellites with Canadian Ice Service sea-ice charts (cf. Agnew and Howell, 2002; Fetterer *et al.*, 2008) to assemble a new sea-ice time series for the period 1971–2007. The new record shows "there has clearly not been a continuous trend in the [time of sea-ice breakup] data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date." The authors observe an increase in regional southwesterly winds during the first three weeks of June, with a corresponding increase in surface temperature, were the likely causes of the earlier breakup.

A necessary longer-term context for considering changes in sea ice has been provided by the reconstruction by Vare *et al.* (2009) of spring sea-ice trends in the central Canadian Arctic Archipelago over the past 1,200 years. These authors applied the biomarker IP25, using a technique developed by Belt *et al.* (2007). IP25 is a mono-unsaturated highly branched isoprenoid synthesized by sea-ice diatoms that live in sediments on the seabed below sea ice, the abundance of which varies according to the degree of ice cover. Using a core from Barrow Strait (74°16.05'N, 91°06.38'W), Vare *et al.* measured a variety of proxy data that included IP25, other organic biomarkers, stable isotope composition of bulk organic matter, benthic foraminifera, particle size distributions, and ratios of inorganic elements.

Vare *et al.* documented a decrease in spring sea ice between approximately 1,200 and 800 years before present, followed by an increase in ice over the last 400 years of their record (between 800 and 400 years BP). That the area of sea ice was less during the Medieval Warm Period and more during the Little Ice Age is a result that could have been expected. Nonetheless, together with the demonstration by Frauenfeld *et al.* of the presence also of multidecadal cycles in sea-ice area, this result confirms many other studies that suggest Arctic sea ice is widely variable and the variability is a manifestation of known natural climatic rhythmicities.

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Earlier research

Clearly, the science pertaining to causes of Arctic sea-ice loss is not settled, as confirmed by the following other recent studies that address the issue.

- Rothrock *et al.* (1999) used submarine sonar measurements to establish that Arctic sea ice in the mid-1990s had thinned by about 42 percent of the average 1958–1977 thickness. The IPCC reported this result, but then commented more recent studies have found the reduction in ice thickness occurred abruptly before 1991, rather than being gradual, and acknowledged “ice thickness varies considerably from year to year at a given location and so the rather sparse temporal sampling provided by submarine data makes inferences regarding long term change difficult” (IPCC 2007, p. 353).
- Johannessen *et al.* (1999) analyzed Arctic sea ice extent over the period 1978–1998 and found it to have decreased by about 14 percent. The change occurred rather abruptly over a single period of not more than three years (1987/88–1990/91) and possibly only one year (1989/90–1990/91). This finding led them to suggest ice cover might be in a state of transition which, if continued, “may lead to a markedly different ice regime in the Arctic,” as was also suggested by Vinnikov *et al.* (1999).
- Winsor (2001) analyzed a more comprehensive set of Arctic sea-ice data obtained from a transect of six submarine cruises conducted between 1991 and 1997. The transect data reveal mean Arctic sea-ice thickness had remained almost constant over the period of study. Data from the North Pole showed little variability, and a linear regression of the data revealed a “slight increasing trend for the whole period.” Combining these results with those from earlier studies, Winsor concludes “mean ice thickness has remained on a near-constant level around the North Pole from 1986 to 1997.”
- Parkinson (2000b) utilized satellite-derived data regarding sea-ice extent to calculate changes for the periods 1979–1990 and 1990–1999. In seven of the nine regions into which he divided the Arctic for his analysis, the “sign of the trend reversed from the 1979–1990 period to the 1990–1999 period,” indicative of the ease with which decadal trends are often reversed in this part of the world.
- Grumet *et al.* (2001) point out recent trends in Arctic sea-ice cover provide only “out of context” results, because their brevity does not allow for the consideration of interdecadal or multidecadal variability. Modern measurements of sea ice are simply available for too short a period for a climate trend to be demonstrated.

  To overcome this problem, Grumet *et al.* developed a 1,000-year record of spring sea-ice conditions in Baffin Bay using sea-salt proxy records from an ice core from the Penny Ice Cap, Baffin Island. Their record demonstrates a period of reduced sea ice during the eleventh–fourteenth centuries, after which enhanced sea-ice conditions prevailed during the next 600 years. During the final (twentieth) century of the record period, “sea-ice conditions in the Baffin Bay/Labrador Sea region, at least during the last 50 years, are within ‘Little Ice Age’ variability.”
- Comiso *et al.* (2001) used 1979–1998 satellite imagery to analyze variability in the Odden ice tongue—a winter ice-cover blanket in the Greenland Sea with a length of about 1,300 km and an area up to 330,000 km^2. Surface air temperature data from nearby Jan Mayen Island provided the necessary meteorological record. Trend analyses revealed the ice tongue has exhibited no statistically significant change over the 20-year period considered. However, a proxy reconstruction of the Odden ice tongue for the

past 75 years suggested it was "a relatively smaller feature several decades ago," due to the warmer temperatures that prevailed at that time.

- In another study of Arctic climate variability, Omstedt and Chen (2001) obtained a proxy record of the annual maximum extent of sea ice in the Baltic Sea over the period 1720–1997. They report a significant decline in sea ice around 1877, with greater variability in sea-ice extent in the preceding, colder, 1720–1877 period than in the ensuing, warmer, 1878–1997 period.
- Jevrejeva (2001) reconstructed an even longer record of Baltic sea-ice variability by summarizing historical data for the annual date of ice breakup at the northern port of Riga, Latvia, for 1529–1990. The historical time series was best described by a fifth-order polynomial, which identified four distinct periods of climatic transition: 1530–1640, warming with a tendency toward earlier ice breakup of nine days/century; 1640–1770, cooling with a tendency toward later ice breakup of five days/century; 1770–1920, warming with a tendency toward earlier ice breakup of 15 days/century; and 1920–1990, *cooling* with a tendency toward later ice breakup of 12 days/century.
- Vinje (2001) studied a wide area of Nordic seas (the Greenland, Iceland, Norwegian, Barents, and Western Kara Seas) and determined "the extent of ice in the Nordic Seas measured in April has decreased by 33% over the past 135 years." Nearly half of this reduction occurred over the period 1860–1900, which spans a period during which atmospheric CO_2 concentration rose by only 7 ppm, and a later time (of sea-ice decline, as it happens) when CO_2 concentration rose by more than 70 ppm. Vinje's study clearly suggests the increase in the air's CO_2 content over the past 135 years has had nothing to do with changes in sea-ice cover.
- In a similar study of the Kara, Laptev, East Siberian, and Chuckchi Seas, based on newly available long-term Russian observations, Polyakov *et al.* (2002) found fast-ice thickness trends in the different seas were "relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level," and these smaller-than-expected trends in sea-ice cover "do not support the hypothesized polar amplification of global warming,"
- Similarly, in a study published the following year, Polyakov *et al.* (2003) report "over the entire Siberian marginal-ice zone the century-long trend is only -0.5% per decade," while "in the Kara, Laptev, East Siberian, and Chukchi Seas the ice extent trends are not large either: -1.1%, -0.4%, +0.3%, and -1.0% per decade, respectively." Moreover, they say "these trends, except for the Chukchi Sea, are not statistically significant."
- Holloway and Sou (2002), employing data-fed model runs, found "no linear trend [in Arctic sea ice volume] over 50 years is appropriate" over the last half of the twentieth century, noting their results indicated "increasing volume to the mid-1960s, decadal variability without significant trend from the mid-1960s to the mid-1980s, then a loss of volume from the mid-1980s to the mid-1990s." They conclude "the volume [of sea ice] estimated in 2000 is close to the volume estimated in 1950."
- Cavalieri *et al.* (2003) extended prior satellite-derived Arctic sea ice records several years back in time by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets. For the newly extended period of 1972–2002, they determined Arctic sea ice extent had declined at a mean rate of $0.30 \pm 0.03 \times 10^6$ km^2 per decade, and for the shortened period from 1979–2002 they found a mean rate of decline of $0.36 \pm 0.05 \times 10^6$ km^2 per decade; i.e., a rate 20 percent greater than the full-period rate. Serreze *et al.* (2002) also determined the downward trend in Arctic sea ice extent during the passive microwave era culminated with a record minimum value in 2002.
- Laxon *et al.* (2003) used an eight-year time series (1993–2001) of Arctic sea-ice thickness data derived from measurements of ice freeboard made by radar altimeters carried aboard ERS-1 and 2 satellites. The latitudes, between 65° and 81.5°N, covered the entire circumference of the Arctic Ocean, including the Beaufort, Chukchi, East Siberian, Kara, Laptev, Barents, and Greenland Seas. The measurements revealed "an interannual variability in ice thickness at higher frequency, and of greater amplitude, than simulated by regional Arctic models," undermining "the conclusion from numerical models that changes in ice thickness occur on much longer timescales than changes in ice extent." The researchers also showed "sea ice mass can change by up to 16% within one year," all of which "contrasts with the concept of a slowly dwindling ice pack, produced by greenhouse warming."

Laxon *et al.* show errors are present in current simulations of Arctic sea ice and conclude, "until models properly reproduce the observed high-frequency, and thermodynamically driven, variability in sea ice thickness, simulations of both recent, and future, changes in Arctic ice cover will be open to question."

- Pfirman *et al.* (2004) analyzed Arctic sea-ice drift dynamics for 1979–1997 using monthly fields of ice motion obtained from the International Arctic Buoy Program. Their analysis indicated sea ice formed over shallow Arctic seas is transported across the central basin to be exported primarily through Fram Strait and, to lesser degrees, the Barents Sea and Canadian Archipelago. Within the central Arctic, the ice travel times for this journey averaged 4.0 years from 1984–85 through 1988–89, but only 3.0 years from 1990–91 through 1996–97. The enhanced rate of modern ice export to Fram Strait from the Beaufort Gyre reduced the amount of thick-ridged ice within the Arctic central basin of the Arctic and helped produce the sea-ice thinning observed in the 1980s and 1990s. Pfirman *et al.* comment the rapid change in ice dynamics between 1988 and 1990 was a "response to a weakening of the Beaufort high pressure system and a strengthening of the European Arctic low (a shift from lower North Atlantic Oscillation/Arctic Oscillation to higher NAO/OA index) [Walsh *et al.*, 1996; Proshutinsky and Johnson, 1997; Kwok, 2000; Zhang *et al.*, 2000; Rigor *et al.*, 2002]."
- Kwok (2004) used QuikSCAT backscatter, MY fractions from RADARSAT, and the record of ice export from satellite passive microwave observations to study Arctic sea-ice changes for 1999–2003. Their results show the coverage of Arctic MY sea ice at the beginning of each year of the study was 3,774 x 103 km2 in 2000, 3,896 x 103 km2 in 2001, 4,475 x 103 km2 in 2002, and 4,122 x 103 km2 in 2003, which represents an increase in sea-ice coverage of 9 percent overall.
- Belchansky *et al.* (2004) report the total Arctic January multiyear ice area declined at a mean rate of 1.4 percent per year for the period 1988–2001. In the autumn of 1996, however, they note, "a large multiyear ice recruitment of over 10^6 km^2 fully replenished the previous 8-year decline in total area." This replenishment was followed by an accelerated and compensatory decline during the subsequent four years.Though the period of study is too short to be conclusive, Kwok (2004) reports 75 percent of the interannual variation in January sea-ice area was explained by linear regression on two atmospheric parameters: the previous winter's Arctic Oscillation index (a proxy for melt duration) and the previous year's average sea level pressure gradient across the Fram Strait (a proxy for annual ice export).
- Heide-Jorgensen and Laidre (2004) examined changes during 1979–2001 in the fraction of open water found within various pack-ice microhabitats of Foxe Basin, Hudson Bay, Hudson Strait, Baffin Bay-Davis Strait, northern Baffin Bay, and Lancaster Sound over a 23-year interval (1979–2001), using remotely sensed microwave measurements of sea-ice extent. Foxe Basin, Hudson Bay, and Hudson Strait showed small increasing trends in the fraction of open water, with the upward trends at all microhabitats studied ranging from 0.2% to 0.7% per decade. In contrast, in Baffin Bay-Davis Straight and northern Baffin Bay the open-water trend was downward, and at a mean rate for all open-water microhabitats studied of fully 1% per decade, and in Lancaster Sound the open-water trend was also downward, this time at a mean rate of 0.6% per decade.

In comparison with these open water changes, Heide-Jorgensen and Laidre report "increasing trends in sea ice coverage in Baffin Bay and Davis Strait (resulting in declining open-water) were as high as 7.5 percent per decade between 1979–1999 (Parkinson *et al.*, 1999; Deser *et al.*, 2000; Parkinson, 2000a,b; Parkinson and Cavalieri, 2002)," and comparable significant increases were detected back to 1953 along the West Greenland coast by Stern and Heide-Jorgensen (2003).

- Bamber *et al.* (2004) used high-accuracy ice-surface elevation measurements (from Krabill *et al.*, 2000) to evaluate 1996–2002 elevation changes in the largest icecap in the Eurasian Arctic—Austfonna, on the island of Nordaustlandet in northeastern Svalbard. The authors discovered the central and highest-altitude area of the icecap, 15 percent of its total area, "increased in elevation by an average of 50 cm per year between 1996 and 2002," while "to the northeast of this region, thickening of about 10 cm per year was also observed." The highest of these growth rates represents as much as a 40 percent increase in accumulation rate (Pinglot *et al.*, 2001).

Bamber *et al.* conclude the best explanation for the dramatic increase in icecap growth over the six-year study period is a large increase in precipitation associated with a concomitant reduction in sea-ice cover in this sector of the Arctic. They characterize the situational change by saying it simply represents the transfer of ice from the top of the sea (in this case, the Barents Sea) to the top of the adjacent land (the Austfonna icecap).

- Divine and Dick (2006) used historical April-August ice observations from Iceland, Greenland, Norwegian, and Barents Seas between 30°W to 70°E to construct time series of ice-edge positions for 1750–2002. The results showed the presence of oscillations in ice cover with periods of about 60 to 80 years and 20 to 30 years, superimposed on a continuous negative trend corresponding to the "persistent ice retreat since the second half of the 19th century." This retreat began well before anthropogenic CO_2 emissions could have had a measurable effect on Earth's climate.

- Gagnon and Gough (2006) analyzed sea-ice variability in Hudson Bay, Canada (cf. Parkinson *et al.*, 1999) using data from 13 stations located along the shoreline of Hudson Bay (seven) and in surrounding nearby lakes (six). They compiled long-term weekly measurements of ice thickness and associated weather conditions for the period 1963–1993, discovering a statistically significant thickening of the ice cover over time occurred in western Hudson Bay, while a small, non-significant thinning occurred on the eastern side. These findings contradict the projections from general circulation models and also "the reduction in sea-ice extent and thickness observed in other regions of the Arctic."
- Over the longer time scale, a study by Eldrett *et al.* (2007) provides further evidence that the IPCC's view of melting sea ice is wrong. They used dynocyst fossils and palaeomagnetic dating to generate a new stratigraphy for three key northern Deep Sea Drilling Project/Ocean Drilling Program sites, finding evidence of "extensive ice-rafted debris, including macroscopic dropstones, in late Eocene to early Oligocene sediments from the Norwegian-Greenland Sea that were deposited between about 38 and 30 million years ago." The data "indicate sediment rafting by glacial ice, rather than sea ice, and point to East Greenland as the likely source," thus suggesting "the existence of [at least] isolated glaciers on Greenland about 20 million years earlier than previously documented."

What is particularly interesting about these findings, as Eldrett *et al.* describe them, is they indicate the presence of glacial ice on Greenland at a time when ocean bottom-water temperatures were 5–8°C warmer and atmospheric CO_2 concentrations as much as four times greater than they are today.

Conclusions

The papers discussed above provide a litany of detailed findings as to the variability of Arctic sea-ice cover in association with natural changes in atmospheric, oceanographic, or ice dynamics. So far as specific changes are concerned—for example the widely reported thinning of Arctic sea ice during the 1990s—no evidence exists that such changes were forced by an increase in atmospheric CO_2 content.

Instead, the oscillatory behavior reported in so many ice studies implies the existence of "close connections between the sea ice cover and major oscillatory patterns in the atmosphere and oceans" (Parkinson, 2000b). This includes, *inter alia*, connections with the North Atlantic Oscillation (e.g., Hurrell and van Loon, 1997; Johannessen *et al.*, 1999; Kwok and Rothrock, 1999; Deser *et al.*, 2000; Kwok, 2000; Vinje, 2001); the spatially broader Arctic Oscillation (e.g., Deser *et al.*, 2000; Wang and Ikeda, 2000); the Arctic Ocean Oscillation (Polyakov *et al.*, 1999; Proshutinsky *et al.*, 1999); the "see-saw" in winter temperatures observed between Greenland and northern Europe (Rogers and van Loon, 1979); and an interdecadal Arctic climate cycle (Mysak *et al.*, 1990; Mysak and Power, 1992).

As concluded by Parkinson (2002), "The likelihood that Arctic sea ice trends are the product of such natural oscillations provides a strong rationale for considerable caution when extrapolating into the future the widely reported decreases in the Arctic ice cover over the past few decades or when attributing the decreases primarily to global warming."

No substantial research study, including the papers discussed above, has demonstrated the level of sea ice in the Arctic Ocean stood at some "ideal" level prior to the Industrial Revolution. Instead, it is manifestly obvious that Arctic sea-ice cover varies dramatically and naturally over quite short periods of geological time. It is also clear Arctic fauna and flora, including the iconic polar bear, are well adapted to deal with the environmental exigencies that result. Regarding environmental policy formulation, it has never been shown that a change in sea-ice cover from, say, its 1850 (preindustrial) level, in either direction, would be a net positive or a net negative from either an environmental or human economic perspective.

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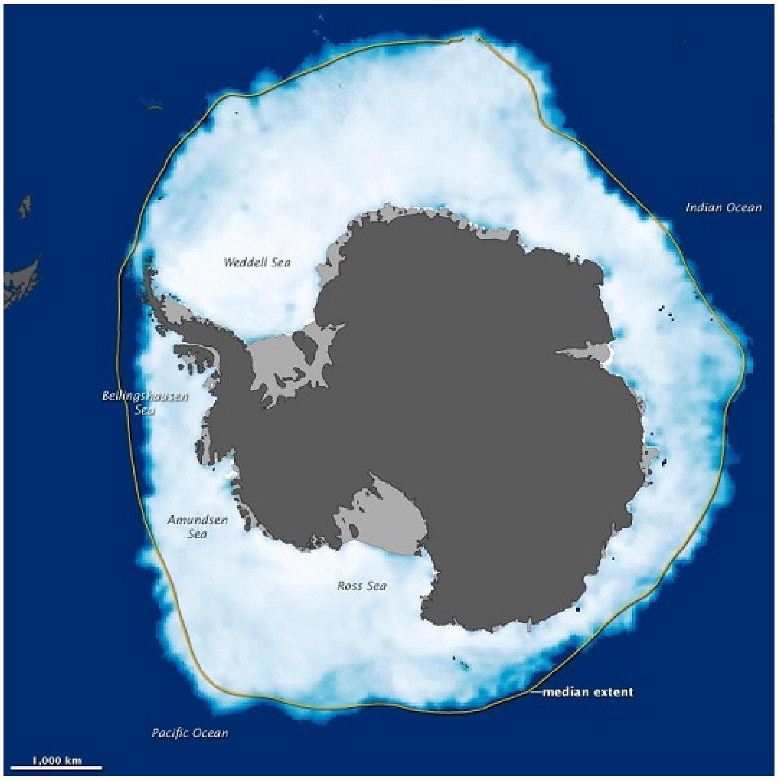
5.10.2 Antarctic Sea Ice

Antarctic sea ice behavior continues to defy the expectations of those who believe that it should be shrinking rapidly under the influence of human-induced global warming (Figure 5.10.2.1). This is not a new finding, and other studies that have addressed this issue are listed below.

Landfast sea ice (fast ice) is sea ice held stationary by being attached to coastal features such as a rocky shoreline, glacier tongue, ice shelf, or grounded iceberg or shoal. Such fast ice is “a preeminent feature of the Antarctic coastal zone and an important interface between the ice sheet and pack ice/ocean” (Fraser *et al.*, 2012). Variability in fast ice extent is often viewed as a sensitive indicator of climate change (Murphy *et al.*, 1995; Heil *et al.*, 2006; Mahoney *et al.*, 2007).

Fraser *et al.* (2012) developed a high-resolution time series of landfast sea ice extent along the East Antarctic coast for the period March 2000–December 2008 using data from the MODIS (Resolution Imaging Spectroradiometer) satellite. The ice area study across East Antarctica (10°W to 172°E) revealed a statistically significant increase of 1.43 ± 0.3% per year, this trend agreeing with other short-term regional trends in overall sea ice (pack ice + fast ice) for different sectors of the coast (Cavalieri and Parkinson, 2008; Comiso, 2009).

Pezza *et al.* (2012) also report a modest increasing trend in sea-ice area around Antarctica over the era of satellite coverage, as documented by Watkins and Simmonds (2000), Zwally *et al.* (2002), Parkinson (2004), Turner *et al.* (2007), and Comiso and Nishio (2008). Pezza *et al.*’s broader study derived a history of Antarctic sea ice for 1979–2008, based upon remotely sensed data from the NASA’s Nimbus-7 SMMR and DMSP SSM/I passive microwave satallites. The results showed modest trends of increasing sea ice during all seasons, with the trends over spring and autumn being the most pronounced, involving an increase of about half-a-million square kilometers over the whole period. This equates with a 2–3 percent increase in sea-ice area during winter and spring and a 5–7 percent increase during summer. Pezza *et al.* report “the greatest [sea ice area] on record occurred during the 2007–2008 summer” when an increase in area of 8 percent occurred.



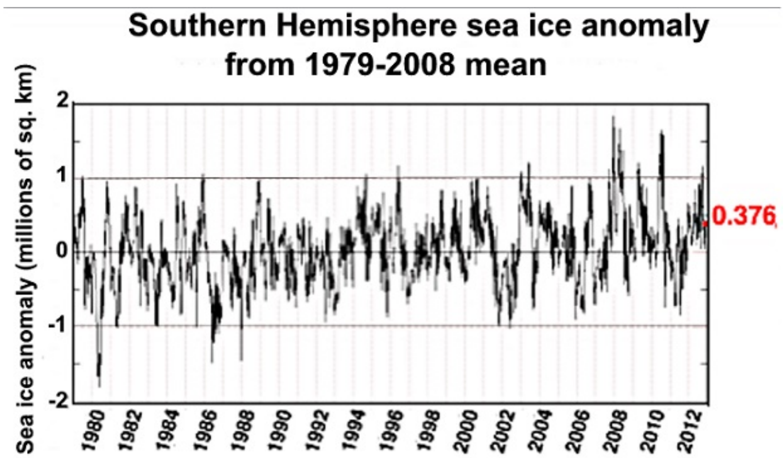


Figure 5.10.2.1. ABOVE Record sea ice area around Antarctica, attained in 2012 (NASA, 2012). BELOW Increase in Antarctic sea ice area since 1979 (graph from *Cryosphere Today*, University of Illinois).

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Earlier Research

Antarctic sea ice behavior continues to defy the expectations of those who believe it should be shrinking rapidly under the influence of human-induced global warming. This is not a new finding;

other studies that have addressed this issue are summarized below.

- Watkins and Simmonds (2000) analyzed trends in sea ice that surrounds Antarctica using data for 1987–1996 collected by the Special Sensor Microwave Imager (SSM/I) on United States meteorological satellites. Statistically significant increases in the area and extent of sea ice[3] were recorded over the period studied, and when the new data were combined with results for the preceding period of 1978–1987, sea ice continued to show increases over the summed period (1978–1996).
- Watkins and Simmonds' findings that Southern Ocean sea ice has increased in area, extent, and season length since at least 1978 are supported by other studies. Hanna (2001) provided an analysis of sea ice cover based on SSM/I data for 1987–1999 and found "an ongoing slight but significant hemispheric increase of 3.7 ± 0.3% in extent and 6.6 ± 1.5% in area." Parkinson (2002) utilized satellite passive-microwave data to map the length of the sea-ice season throughout the Southern Ocean for each year of the period 1979–1999, finding a "much larger area of the Southern Ocean experienced an overall lengthening of the sea-ice season … than experienced a shortening." Updating the analysis two years later for the period 1978–2002, Parkinson (2004) reported a linear increase in 12-month running means of Southern Ocean sea ice extent of 12,380 ± 1,730 km^2 per year.
- Elderfield and Rickaby (2000) conclude the sea-ice cover of the Southern Ocean during glacial periods may have been as much as double the coverage of modern winter ice. They suggest by restricting communication between the ocean and atmosphere, sea-ice expansion provides a mechanism for reduced CO_2 release by the Southern Ocean and thereby lower glacial atmospheric CO_2 during glaciations.
- Yuan and Martinson (2000) analyzed Special SSM/I data together with data derived from brightness temperatures measured by the Nimbus-7 Scanning Multichannel Microwave Radiometer, finding, among other things, the mean trend in the latitudinal location of the Antarctic sea-ice edge over the prior 18 years was an equatorward expansion of ice by 0.011^O of latitude per year.
- Zwally *et al.* (2002) also utilized passive-microwave satellite data to study Antarctic sea ice trends. Over the 20-year period 1979–1998, they report the sea ice extent of the entire Southern Ocean increased by 11,181 ± 4,190 square km per year, or by 0.98 ± 0.37% per decade, while sea-ice area increased by nearly the same amount: 10,860 ± 3,720 square km per year, or by 1.26 ± 0.43% per decade. They observed the variability of monthly sea-ice extent declined from 4.0% over the first 10 years of the record to 2.7% over the last 10 years.
- Vyas *et al.* (2003) analyzed data from the multichannel scanning microwave radiometer carried aboard India's OCEANSAT-1 satellite for the period June 1999–May 2001, which they combined with data for the period 1978–1987 derived from passive microwave radiometers aboard earlier Nimbus-5, Nimbus-7, and DMSP satellites to study secular trends in sea-ice extent about Antarctica over the period 1978–2001. This work revealed a mean rate of increase in sea-ice extent for the entire Antarctic region of 0.043 million km² per year. Vyas *et al.* note also "the increasing trend in the sea ice extent over the Antarctic region may be slowly accelerating in time, particularly over the last decade," commenting the "continually increasing sea ice extent over the Antarctic Southern Polar Ocean, along with the observed decreasing trends in Antarctic ice surface temperature (Comiso, 2000) over the last two decades, is paradoxical in the global warming scenario resulting from increasing greenhouse gases in the atmosphere."
- In a similar study, Cavalieri *et al.* (2003) extended prior satellite-derived Antarctic sea ice records several years by bridging the gap between Nimbus 7 and earlier Nimbus 5 satellite data sets with National Ice Center digital sea ice data. They found between 1977 and 2002 sea-ice extent around Antarctica increased at a mean rate of 0.10 ± 0.05 x 10^6 km² per decade.
- Similarly, Liu *et al.* (2004) used sea-ice concentration data from the scanning multichannel microwave radiometer on the Nimbus 7 satellite and the spatial sensor microwave/imager on several defense meteorological satellites to develop a quality-controlled history of Antarctic sea ice variability for 1979–2002. They found "overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (of ~4,801 km²/yr)." In addition, they determined the total Antarctic sea ice increased by ~13,295 km²/yr, at a greater than 95% confidence

[3] The *area* of sea ice is defined as the summed area of ice not including enclosed gaps and leads; the *extent* of sea ice is always a greater number and is measured inclusive of gaps and leads.

level.

- Laine (2008) determined 1981–2000 trends of Antarctic sea-ice concentration and extent based on the Scanning Multichannel Microwave Radiometer (SSMR) and SSM/I for the spring-summer period of November/December/January. These analyses were carried out for the continent as a whole as well as for five longitudinal sectors emanating from the South Pole. Laine concludes "sea ice concentration shows slight increasing trends in most sectors, where the sea ice extent trends seem to be near zero." Laine also reports "the Antarctic region as a whole and all the sectors separately show slightly positive spring-summer albedo trends."
- Comiso and Nishio (2008) provide updated and improved estimates of trends in Arctic and Antarctic sea ice cover for the period 1978–2006 using data from the Advanced Microwave Scanning Radiometer (AMSR-E), the SSM/I, and the SMMR, where the data from the last two instruments were adjusted to be consistent with the AMSR-E data. Their findings indicate sea-ice extent and area in the Antarctic grew by +0.9 ± 0.2 and +1.7 ± 0.35% per decade, respectively.
- Cavalieri and Parkinson (2008) extend the analyses of sea ice time series reported by Zwally *et al.* (2002) from 20 years (1979–1998) to 28 years (1979–2006), based upon satellite-borne passive microwave radiometer data. The results indicate "the total Antarctic sea ice extent trend increased slightly, from 0.96 ± 0.61% per decade to 1.0 ± 0.4% per decade, from the 20- to 28-year period." Corresponding numbers for Antarctic sea ice area trends were 1.2 ± 0.7% per decade and 1.2 ± 0.5% per decade. Over the last eight years of the study period, both the extent and area of Antarctic sea ice have continued to increase, with the former parameter increasing at a more rapid rate than it did over the 1979–1998 period.

Conclusions

Since they first became available in 1979, satellite-mounted sensors have provided evidence for the multidecadal growth of both pack ice and fast ice across the entire East Antarctic region, and this expansion continues today. These observations contradict the climate modeling that projects decreases in Antarctic sea ice.

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5.10.3 Lake Ice

Floating ice pack responsive to climatic fluctuations forms on large, intracontinental lakes as well as on the ocean, and Wang *et al.* (2010) provide an analysis of 70 years of such floating ice for the Great Lakes of North America. Their study covers the winters of 1972–73 to 2008–09 and comprises an analysis of time series of annual average ice area and basin winter average surface air temperature (SAT) and floating ice cover (FIC) for the Great Lakes, which they remind us "contain about 95% of the fresh surface water supply for the United States and 20% of the world."

The primary data of interest are depicted in Figure 5.10.3.1, which shows after an initial four years of relative warmth and lower annual average ice area, SATs declined and FIC area rose. Then there began a long period of somewhat jagged SAT rise and FIC decline, both of which level out from about 1998 to 2006, after which SAT once again slowly declines and FIC slowly rises. Both parameters terminate at about the same value they exhibited initially.

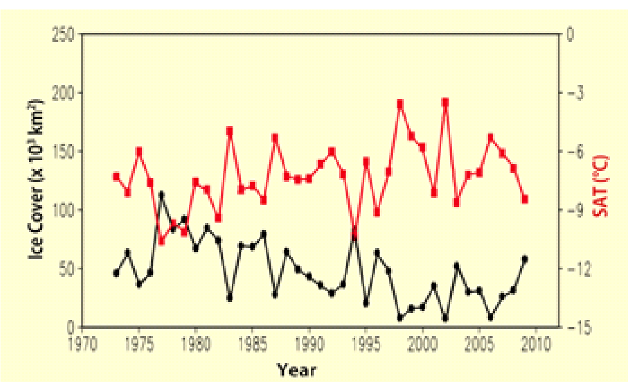

Figure 5.10.3.1. Annual average ice area of the North American Great Lakes and basin winter average surface air temperature (SAT) vs. time. Adapted from Wang, J., Bai, X., and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. *EOS, Transactions, American Geophysical Union* **91**: 41–42.

Conclusions

Wang *et al.* (2010) conclude "natural variability dominates Great Lakes ice cover" and the short-term trends present are "only useful for the period(s) studied." There is therefore no reason to attribute any change in the annual average ice area of the North American Great Lakes to anthropogenic global warming. Similarly, Yoo and D'Odorico (2002) have shown northern high-latitude ice break-up follows a natural multidecadal rhythm rather than conforming to any long-term linear melting trend.

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5.11 Late Pleistocene Glacial History

Geological studies have established that during the most recent major deglaciation since 20,000 years ago, multiple intense and abrupt warmings and coolings, with parallel ice volume changes, occurred throughout the world. This geological record of past climatic events provides an essential context missing from many current discussions of modern ice volume changes and their significance.

The results of oxygen isotope measurements from ice cores in the Greenland and Antarctic ice sheets several decades ago (see Section 5.7) stunned the scientific world (Dansgaard, 1987; Dansgaard and Oeschger, 1989; Dansgaard *et al.*, 1969, 1970, 1971, 1982, 1984, 1989; Jouzel *et al.*, 1987a, b, 1989; Oeschger *et al.*, 1983). Among the surprises was the delineation of multiple abrupt and intense periods of warming and cooling with a 1,500-year periodicity, which have come to be called Dansgaard-Oeschger (or D-O) events. The most precise records of these changes are the ice cores from the Greenland Ice Sheet Project (GISP) and the Greenland Ice Core Project (GRIP), which are especially important because the age of the ice at various levels in the cores has been established by counting annual layers, yielding a very accurate chronology of climatic fluctuations.

The Greenland GISP2 ice core shows temperatures for the past 100,000 years, of which the last 50,000 are presented in Figure 5.11.1 (upper). The later part of the last ice age (50,000–20,000 y BP) was followed by spasmodic and abrupt warming at the start of the Holocene at 11,700 y BP. More than a dozen episodes of abrupt warming and cooling occurred within the past 50,000 years, all of which accords well with other geologic evidence that had previously led to the recognition of several periods of warming and cooling. The named climatic periods, of which the cold Younger Dryas interval is the best known (Figure 5.11.1, lower), were established from geological land studies long before their equivalents were recognized in deep sea mud cores and polar ice cores. In decreasing age, the major post-glacial climatic episodes delineated by geological studies comprise the Oldest Dryas (cold) Period, the Bølling (warm) Period, the Older Dryas (cold) Period, the Allerød (warm) Period, the Inter-Allerød (cold) Period, and the Younger Dryas (cold) Period.

The *Oldest Dryas Period* lasted between about 18,000 and 15,000 years BP (Roberts, 1998), with ^{14}C dates from the northwest shore of Lake Neuchâtel in Switzerland placing its termination at 14,650 y BP. Data derived from isotope variation of nitrogen and argon trapped in Greenland ice samples gives a second high-resolution date for the sharp temperature rise that ended it, 14,670 y BP. The significance of the Oldest Dryas is the abruptness of the warming that terminated it, during which temperatures in Greenland rose about 13°C in only a few centuries (Grootes and Stuiver, 1997; Cuffy and Clow, 1997).

The Greenland oxygen isotope record shows the *Bølling Warm Period* to lie between 14,600 and 14,100 BP. Abrupt, intense warming 14,500 years ago resulted in sudden wholesale melting of the huge continental ice sheets that covered North America, Europe, and Russia, and also an extensive retreat of alpine glaciers in discrete mountainous areas. This warming was remarkable because of both its abrupt onset and its intensity. Temperatures in Greenland rose ~12° C (which equals almost the total cooling of the late Pleistocene glaciation) to near present-day levels in about one century. As a result of the sudden, intense warming and melting, sea level rose sharply by perhaps as much as 18 m (Deschamps *et al.*, 2012). Although these temperature changes are cited for Greenland, simultaneous glacial retreats all over the world indicate the Bølling warming was global and characterized by temperatures at near-modern levels.

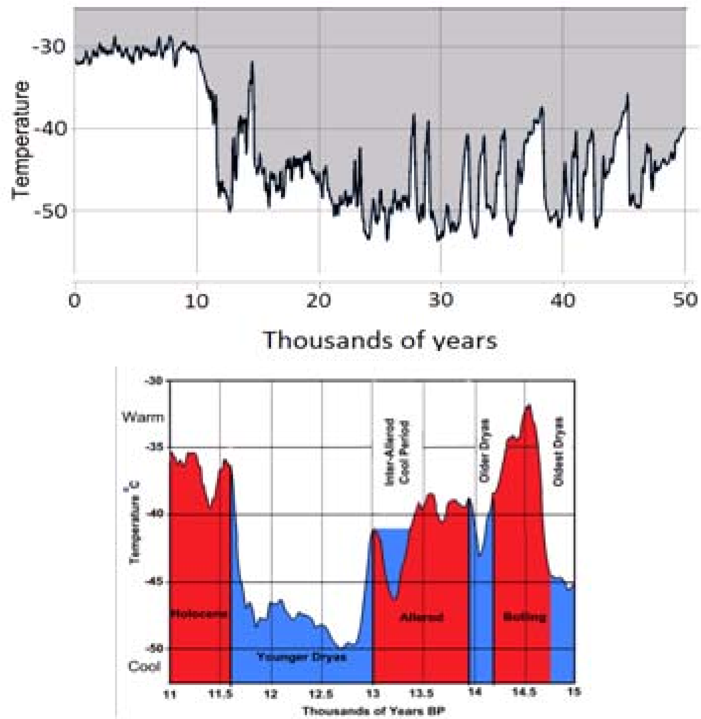

Figure 5.11.1. ABOVE. Greenland GISP2 air temperature curve for the past 50,000 years. Adapted from Cuffey, K.M. and Clow, G.D. 1997. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research* **102**: 26,383–26,396. BELOW. Late glacial temperature fluctuations in the GISP2 Greenland ice core. Red = warm periods, blue = cold periods. Data from Cuffy and Clow (1997) and Alley, R.B. 2000, The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

The Bølling was terminated by temperatures plummeting again from the thermal maximum by about 11°C in a few hundred years, thus initiating the *Older Dryas Period* from 14,300 to 14,000 BP. Temperatures returned to near full glacial level, and glaciers halted their rapid retreat.

About 14,000 years BP, temperatures rose abruptly again, and the *Allerød Warm Period* began and lasted until 12,800 years BP. Though the Allerød was not as warm as today, or as during the Bølling, the rate of warming was still rapid, at ~4.5°C/century. The interstadial ended abruptly with a cold period that reduced temperatures back to near-glacial levels within a decade.

Near the end of the Allerød warm period, temperatures dropped precipitously by ~8°C in about a century, to delineate what is called the *Inter-Allerød (cold) Period* (Grootes and Stuiver, 1997; Cuffy and Clow, 1997). Temperatures returned to nearly full Ice Age levels but persisted for only a few hundred years, so glaciers halted their retreat but did not rebuild to former extents. Then, just as suddenly as it had cooled, abrupt warming of ~5°C occurred, and temperatures returned to Allerød levels. In the Southern Hemisphere, the Allerød warming was interrupted by a colder period known as the *Antarctic Cold Reversal,* which lasted from ~13,500- 13,000 year BP (Grootes and Stuiver, 1997; Cuffy and Clow, 1997). This reversal is well documented in Antarctic ice cores and also by glacial advances that occurred in New Zealand and are represented by the Birch Hill and Macaulay moraines in the Tekapo Valley of the Southern Alps (Easterbrook *et al.,* 2011).

The *Younger Dryas* is the longest and coldest of several very abrupt climatic changes near the end of the Pleistocene. It comprised a period of cold lasting about 1,300 years and ended as abruptly as it started. At the start of the event, 12,800 years ago, temperatures plunged ~8°C to full glacial levels. Glaciers, including remnants of the continental ice sheets, re-advanced, leaving moraines as footprints of their former presence. The end of the Younger Dryas occurred when temperatures rose sharply by ~12° C over about 50 years, to terminate the Pleistocene ice age about 11,500 years ago.

Radiocarbon and isotope dating of glacial moraines in regions all over the world, and abrupt steps in oxygen isotope ratios in the Greenland and Antarctic ice cores, indicate the Younger Dryas cooling was both globally widespread and synchronous. Evidence of Younger Dryas ice advance is reported from the Scandinavian ice sheet, the North American Laurentide and Cordilleran ice sheets, and the Russian ice sheet. Alpine and icecap glaciers also advanced during Younger Dryas cooling in both the Northern and Southern hemispheres, including many places in the Rocky Mountains of the United States and Canada, the Cascade Mountains of Washington in the United States, the European Alps, the Southern Alps of New Zealand, and the Patagonian Andes Mountains of South America.

The Younger Dryas cooling was not just a single climatic event. Not only did climatic warming and cooling occur both before and after it, but significant climate fluctuations also occurred within the Younger Dryas. That these were global events in both hemispheres is shown not only by correlations between ice cores from Greenland and Antarctica but also by the presence of dated, multiple glacial moraines around the world (Easterbrook *et al.,* 2011).

Figure 5.11.2 shows a plot of oxygen isotope variation within the Younger Dryas. Temperatures fluctuated up and down at least a dozen times, some brief warming periods reaching near-Allerød levels. Radiocarbon and cosmogenic dating of glacial moraines, and abrupt changes in oxygen isotope ratios in ice cores, indicate the Younger Dryas cooling was globally synchronous. That these climatic fluctuations were global in extent is shown by the occurrence of multiple Younger Dryas moraines around the world.

The type locality for the Younger Dryas is in Scandinavia, where the Scandinavian Ice Sheet

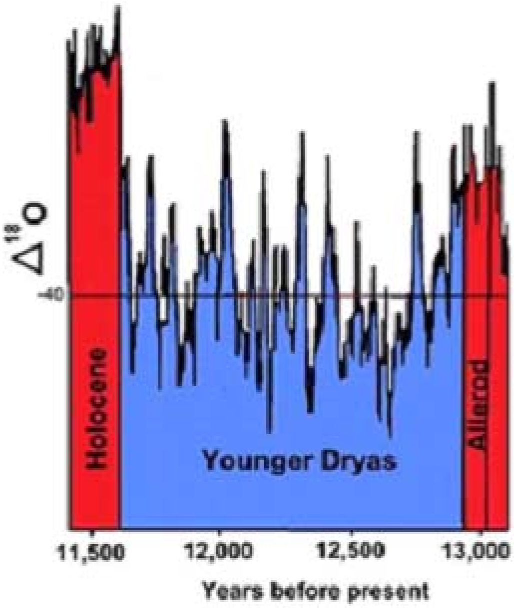

Figure 5.11.2. Oxygen isotope record from the Greenland ice core showing an abrupt temperature drop 12,800 years ago, 1,300 years of cool climate, and sudden warming 11,500 years ago (plotted from data in Grootes and Stuiver, 1997).

deposited two extensive Salpausselka end moraines across southern Finland, the central Swedish moraines, and the Ra moraines of southwestern Norway during the Younger Dryas. ^{14}C dates suggest an age of ~10,700 y BP for the outer Salpausselka moraine and ~10,200 y BP for the inner moraine, very similar to Younger Dryas moraines of the Cordilleran and Ice Sheets in North America.Thus, all three major Pleistocene ice sheets experienced multiple moraine-building episodes during the Younger Dryas.

Multiple Younger Dryas moraines also occur at Loch Lomond in the Scottish Highlands (e.g., Sissons, 1980; Ballantyne, 2002, 2006; Benn and Ballantyne, 2005; Bennett and Boulton, 1993; Rose *et al.*, 1998). Alpine glaciers and icefields in Britain readvanced or re-formed during the Younger Dryas and built extensive moraines at glacial margins. The largest Younger Dryas icefield at this time was the Scottish Highland glacier complex, but smaller alpine glaciers occurred in the Hebrides and Cairngorms of Scotland (Sissons, 1980), in the English Lake District, and in Ireland. The Loch Lomond moraines consist of one to several moraines, sometimes multiple, nested, recessional moraines. Radiocarbon dates constrain the age of the Loch Lomond moraines between 12.9 and 11.5 cal y BP.

Further south, in the Swiss Alps near St. Moritz, a complex moraine system contains two main morainal ridges. The outer moraine has been dated by ^{10}Be, ^{26}Al, and ^{36}Cl at 11.75 ka and the inner moraine at 10.47 ka (Ivy-Ochs *et al.*, 1996, 1999; Kerschner *et al.*, 1999). At Maloja Pass, less than 10 km from Julier Pass, a bog just inside the outermost of three Egesen moraines was ^{14}C dated at 10,700 y B.P. (Heitz *et al.*, 1982).

post-LGM fluctuations of the CIS (Easterbrook, 1963, 1992, 2010; Easterbrook *et al.*, 2007; Kovanen and Easterbrook, 2002). The chronology of the ice margin fluctuations and timing of ice retreat during the Sumas Stade (Figure 5.11.3) are bracketed by 70 radiocarbon dates and tied to morphologic and stratigraphic evidence. The CIS chronology, which

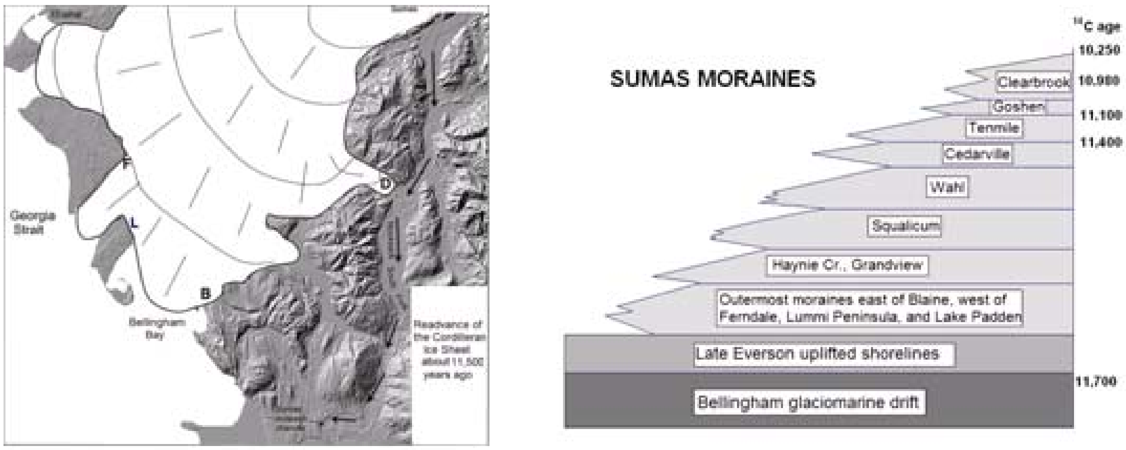

Figure 5.11.3. LEFT Reconstruction of the Cordilleran ice sheet at the end of the Pleistocene, 11,500 ^{14}C yrs. ago, NW Washington USA. RIGHT, Depiction of multiple Younger Dryas moraines from the Cordilleran ice sheet. From Easterbrook, D.J. 2012. Part 2 of Professor Don Easterbrook's concerns about the "Shakun *et al*. paper." Climate Observer [Web site] http://climateobserver.blogspot.com/2012/04/part-2-of-professor-don-easterbrooks.html.

Despite early evidence that a similar late-glacial readvance occurred in western North America (Armstrong, 1960; Easterbrook, 1963; Armstrong *et al.*, 1965), the apparent absence of the marker pollen evidence led some to believe the Younger Dryas did not occur in North America. Recent research has established the effects of the Younger Dryas as widespread at localities in the Pacific Northwest (Easterbrook, 1994a,b, 2002, 2003a,b; Easterbrook and Kovanen, 1998; Kovanen and Easterbrook, 2001, 2002), the Rocky Mountains (Licciardi *et al.*, 2004, Gosse *et al.*, 1995a,b; Easterbrook *et al.*, 2004), and California (Owen *et al.*, 2003). Planktonic microfossil records from the Pacific Northwest and Alaska also confirm the presence of a Younger Dryas event, with alkenone estimates of sea surface temperatures west of Vancouver Island indicating a temperature drop of 3^{O} C (Kienast and McKay, 2001).

Morphologic, stratigraphic, and chronologic evidence of multiple moraines associated with oscillations of the remnants of the Cordilleran Ice Sheet (CIS) in the Fraser Lowland of British Columbia and Washington has revealed multiple closely matches that of the GISP2 and GRIP ice cores from Greenland and sea surface temperatures in the north Pacific (Kienast and McKay, 2001), also compares well with the chronology of post-LGM alpine moraines in the western United States

Elsewhere in North America, Younger Dryas deposits are associated with an advance of the Laurentide Ice Sheet with dated moraine deposition in SW Canada (Grant and King, 1984; Stea and Mott, 1986, 1989); the expansion of cirque glaciers in the Wind River Range, Wyoming (Gosse *et al.*, 1995) and Sawtooth Range, Idaho (Easterbrook *et al.*, 2011); extensive moraine and ice-contact sediment deposition in the North Cascade Mountains (Kovanen and Easterbrook, 2001; Easterbrook *et al.,* 2010); cirque moraines in the Mt. Rainier part of the Cascade Range (Crandell and Miller, 1974); and multiple moraines near Icicle Creek (Page, 1939; Porter, 1976; Long, 1989; Easterbrook *et al.*, 2011).

In the Southern Hemisphere, multiple Younger Dryas moraines occur in the Southern Alps of New Zealand, for example at Arthur's Pass and at Birch Hills along Lake Pukaki. At the latter locality the

Younger Dryas moraines are located ~40 km up-valley from the last glacial maximum moraines. Younger Dryas moraines also occur at Prospect Hills in the Arrowsmith Range (Burrows, 1975) (Figure 5.11.4), and on the west coast of South Island, where wood in the Waihao Loop moraine, deposited by the Franz Josef Glacier about 20 km behind the LGM moraine, has been dated at 11,200 ^{14}C y BP (Mercer, 1982, 1988; Denton and Hendy, 1994).

Conclusions

Since the last glaciation, repeated rapid and often synchronous warmings and coolings have occurred across the globe, accompanied by concomitant glacial retreat and advance. The magnitude and intensity of these climatic fluctuations have been up to 20 times greater than modern warming during the past century.

The Younger Dryas is perhaps the most important of the climatic episodes, and the multiple nature of its moraines in both hemispheres indicates the occurrence of multiple climatic pulses (see Figure 5.11.5). The absence of a time lag between the Northern and Southern Hemisphere glacial fluctuations precludes an oceanic cause such as the North Atlantic Deep Ocean Water hypothesis for the cause of the Younger Dryas. Nor does a singular cosmic impact or volcanic origin seem likely because multiple Dansgaard/Oerscher warming and cooling events have recurred over periods of tens of thousands of years.

The most likely causation of the millennial rhythmicity that modulates major glacial-interglacial episodes is fluctuations in solar activity. What is certain is that none of the events were forced by changes in atmospheric carbon dioxide.

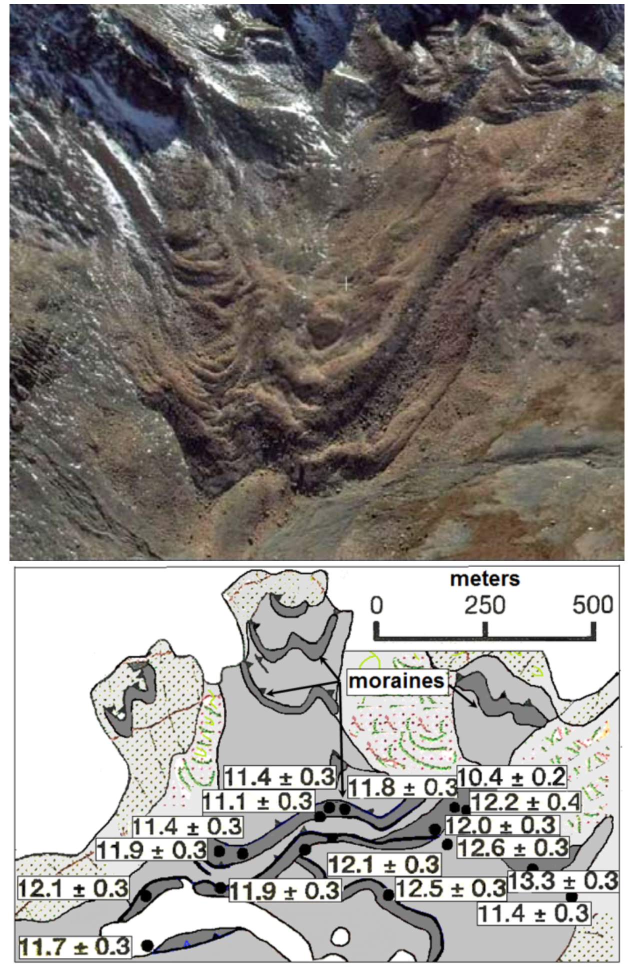

Figure 5.11.4. Moraines of the Younger Dryas ice advance in Irishman Basin, New Zealand Southern Alps. TOP: Aerial photograph. BOTTOM: Cosmogenic dates in thousands of years. Adapted from Kaplan, M.R., Schaefer, J.M., Denton, G.H., Barrell, D.A., Chinn, T.J.H., Putnam, A.E., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A.M. 2010. Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* **3**: 194–197.

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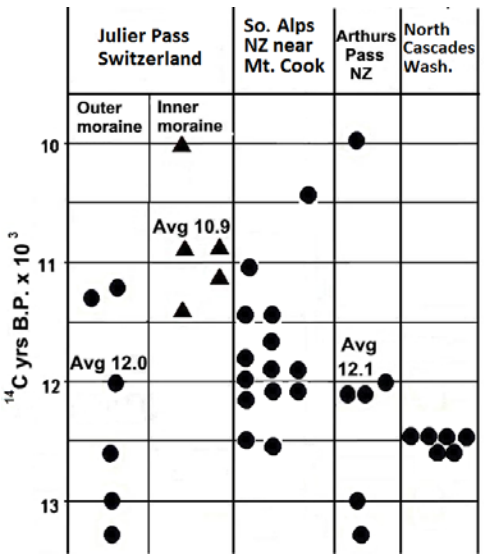

Figure 5.11.5. Ages of Younger Dryas moraines in New Zealand and the Swiss Alps. Adapted from Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., and Schluchter, C. 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* **28**: 2137–2149; and Easterbrook, D.J., Gosse, J, Sherrard, C., Stevemspm, E.B., and Finkel, R. 2011. Evidence for synchronous global climatic events: cosmogenic exposure ages of glaciations. In: *Evidence-Based Climate Science*, Easterbrook, D.J. (Ed.), pp. 53–88.

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5.12 Holocene Glacial History

The climatic changes seen during the late Pleistocene continued, albeit at a lesser amplitude than for Dansgaard-Oescher events, during the last 11,700 years (Holocene Period). Holocene climatic variability is well encapsulated by the temperature curve inferrred from oxygen isotope measurements in Greenland ice cores (see Figure 5.12.1).

The five most important characteristics of the documented variability are the presence of a temperature peak about 2^o C warmer than today during the Holocene climatic optimum, ~8,000 y BP; the general cooling trend that occurred thereafter; the punctuation of the record by 1,500-year-long alternating rhythms of warmer and colder climate (the Bond Cycle, of probable solar origin: Bond *et al.*, 1997; Wanner *et al.*, 2008); that for the great majority of the last 10,000 years temperature has been warmer than today; and that none of the climatic fluctuation during the Holocene was accompanied by parallel fluctuations in carbon dioxide.

A conspicuous larger climatic event occurred 8,200 years ago, when the Holocene record was interrupted by a sudden global cooling that lasted for 200 years (Figure 5.12.2). During this time, alpine glaciers advanced and built moraines (Easterbrook, 2011). Neither the abrupt climatic cooling nor the abrupt warming that followed was accompanied by atmospheric CO_2 changes.

Most of the climatic episodes indicated by the Greenland climate record also were recorded by historic sources. Egyptian records from before the founding of the Roman Empire show a cool climatic period from about 750 to 450 BC, with the Tiber River freezing and snow remaining on the ground for long periods (Singer and Avery, 2007). The Roman Warm Period (200–600 AD) followed, when the Romans wrote of grapes and olives growing farther north in Italy than had been previously possible.

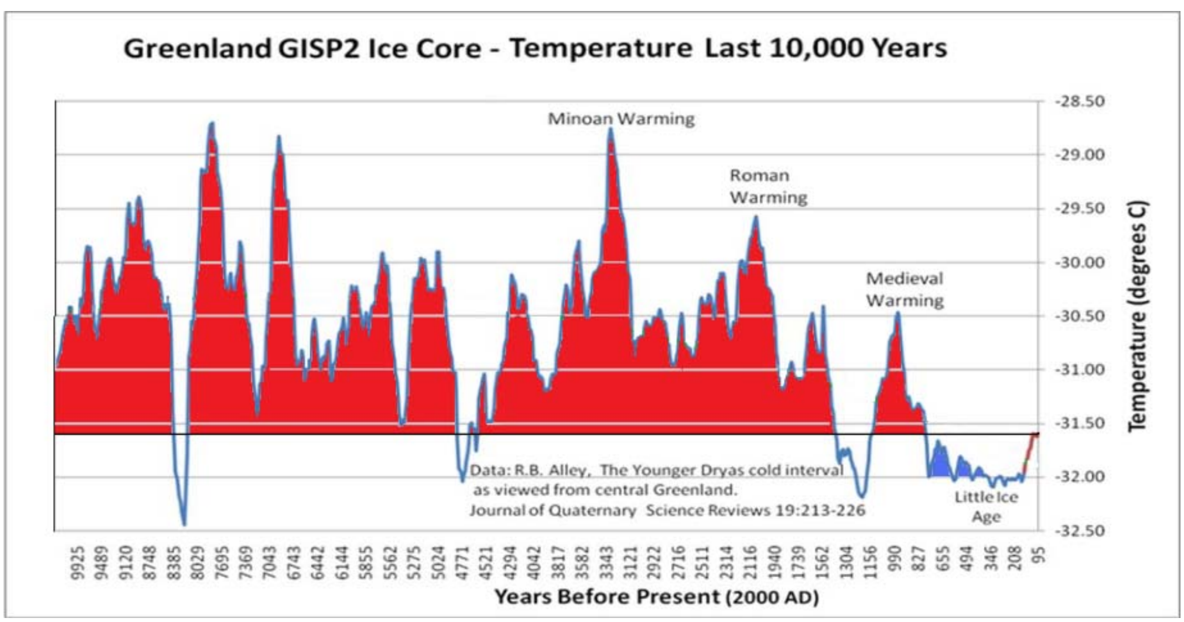

Figure 5.12.1. Temperature over the last 10,000 y from the GISP2 ice core, Greenland. Adapted from Alley, R.B., 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews* **19**: 213–226.

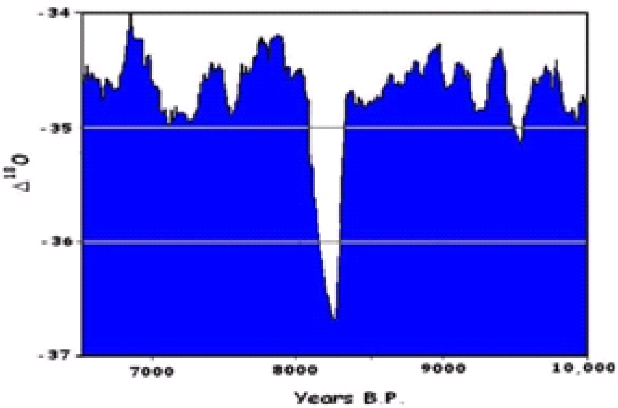

Figure 5.12.2. The 8,200 y BP sudden cooling recorded in oxygen isotope ratios in the GISP2 ice core. Adpated from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO_2 emissions as the primary source of global warming.* Elsevier.

The ensuing Dark Ages Cool Period (440–900 AD) was characterized by marked cooling again, with 540 AD marking a particularly cold year when tree rings were retarded, fruit didn't ripen, and snow fell in summer in Southern Europe. In addition, in 800 AD the Black Sea froze, and in 829 AD the Nile River froze (Oliver, 1973).

The Medieval Warm Period (900–1300 AD) that followed was marked by global temperatures warmer than at present, as indicated by the flourishing of grain crops, elevation of alpine tree lines, and building of many new towns and cities as the European population more than doubled. The Vikings took advantage of the climatic amelioration to colonize Greenland in 985 AD, when milder climates allowed favorable open-ocean conditions for navigation and fishing. Wine grapes were grown about 500 km north of present vineyards in France and Germany, and also in the north of England (Oliver, 1973; Tkachuck, 1983). Wheat and oats were grown around Trondheim, Norway, suggesting climates about one degree C warmer than the present (Fagan, 2009).

After the Medieval Warm Period, temperatures in Europe dropped by as much as ~4° CC in ~20 years as the Little Ice Age (1300-1860 AD) commenced.

Though the overall cold lasted for 400 years, climate rhythmicity was maintained throughout, as manifest by 25 cold-warm oscillations (see Figure 5.12.3). During cold phases, the bitter winters and cool, rainy summers were too cool for satisfactory growth of cereal crops, which resulted in devastating crop failure, famine, and disease. Three years of torrential rains that began in 1315 led to the Great Famine of 1315–1317, and during colder winters the Thames River in London and canals in the Netherlands froze over (Grove, 1988, 2004; Fagan, 2001). Glaciers expanded worldwide during the Little Ice Age (Grove, 2004; Singer and Avery, 2007), with Greenland pack-ice extending well south in the North Atlantic in the thirteenth century (Singer and Avery, 2007). Glacial advances in the Swiss Alps in the mid-seventeenth century gradually encroached on farms and buried entire villages.

Elsewhere in the world, New York Harbor froze in the winter of 1780; sea ice surrounding Iceland

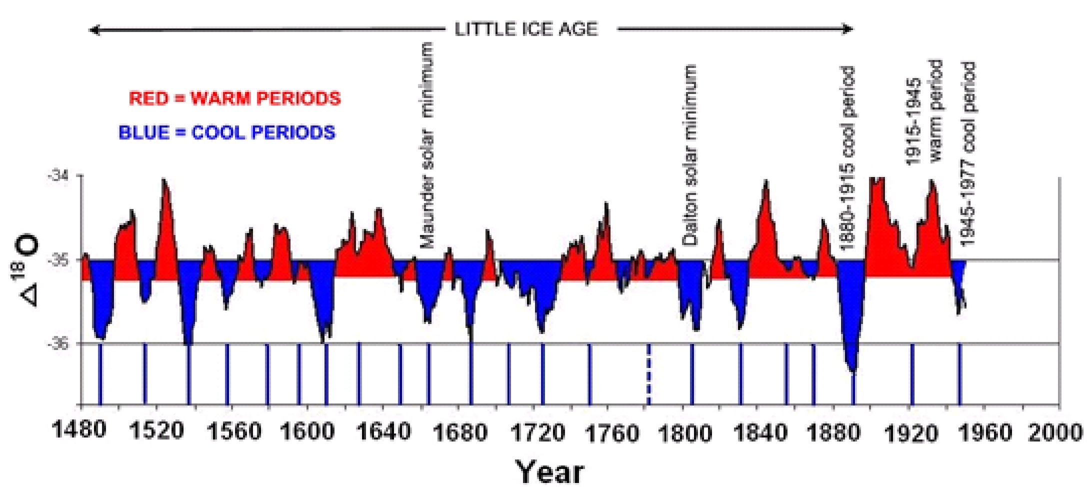

Figure 5.12.3. Oxygen isotope record from the GISP2 Greenland ice core showing more than 25 periods of warming and cooling since 1460. Data from Grootes and Stuiver (1997). Adapted from Easterbrook, D.J. (Ed.) 2011. *Evidence-based climate science: Data opposing CO_2 emissions as the primary source of global warming.* Elsevier.

extended for miles in every direction, closing many harbors; the population of Iceland decreased by half; and the Viking colonies in Greenland died out in the 1400s because food could no longer be grown there.

Conclusions

The rhythmic Holocene 1,500-year temperature changes recorded in the Greenland GISP2 ice core show the magnitude of global warming experienced during the twentieth century falls well within the bounds of previous natural variations. In addition, and especially apparent during late Holocene historical times, a multidecadal climate modulation is apparent that closely approaches the pattern observed also in the twentieth century temperature record. Because late twentieth century warming corresponded to warming limbs of both the multidecadal and the 1,500- year rhythms, it was not unexpected.

In essence, both the rate and magnitude of twentieth century warming are small compared to the magnitude of the profound natural climate reversals over the past 25,000 years (Figure 5.12.4). Most important in the context of the public debate about climate change, none of the larger late Pleistocene and Holocene climatic events were accompanied by any significant parallel change in atmospheric carbon dioxide level. The null hypothesis that twentieth century warming represents natural climate variation therefore remains valid.

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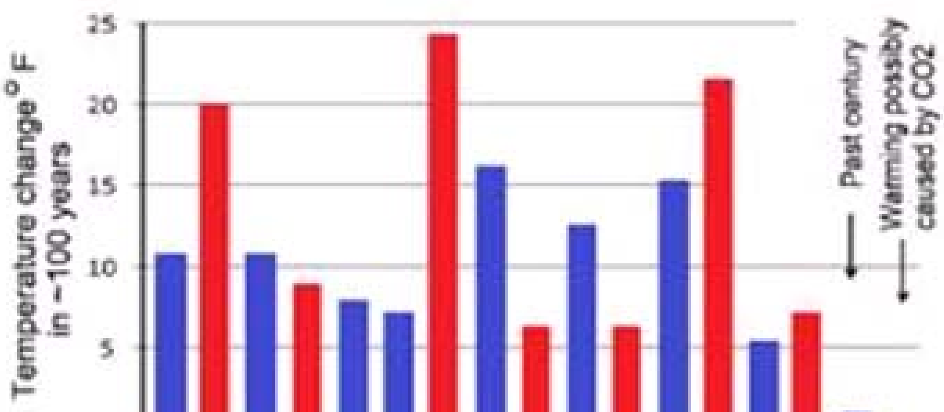

Figure 5.12.4. Magnitudes of the largest warming/cooling events over the past 25,000 years. Temperature changes shown on the vertical axis are rise or fall of temperatures in about a century. Event number 1 happened about 24,000 years ago, and event number 15 is about 11,000 years old. At least three warming events were 20 to 24 times the magnitude of warming over the past century, and four were six to nine times the magnitude of warming over the past century. The magnitude of the only modern warming which might possibly have been caused by CO_2 (1978–1998) is insignificant compared to the earlier periods of warming. Plotted from data in Cuffy and Clow (1997) and Alley (2000).

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6

Observations: The Hydrosphere and Ocean

Willem de Lange (New Zealand)

Robert M. Carter (Australia)

Introduction

6.1. The Hydrosphere
- Key Findings
- 6.1.1. Precipitation
- 6.1.2. Monsoons
- 6.1.3. Snow
- 6.1.4. Evaporation
- 6.1.5. Drought
- 6.1.6. Rivers and Streamflow

6.2. The Oceans
- Key Findings
- 6.2.1. Sea Level Change
- 6.2.2. Ocean Heat
- 6.2.3. Ocean Circulation

Introduction

The hydrosphere comprises the combined mass of water that occurs on or near Earth's surface. It includes oceans, lakes, rivers, and streams. Because it covers about 70 percent of Earth's surface area, the hydrosphere plays a vital role in sustaining communities of water-inhabiting plants and animals.

The processes and characteristics of the hydrosphere change through time in response to the internal dynamics of the climate system; i.e., the chaotic dynamics of oceanographic and meteorological processes. In addition to this internal, natural variation, aspects of the hydrosphere also change in response to external climate change forcings, some of which are natural (e.g., changed solar insolation) and some of human origin (e.g., greenhouse gas forcing). This distinction between natural and anthropogenic forcings, which applies to all aspects of Earth's climate system, is easy to draw in principle, but in practice it has proved difficult to establish that any specific changes documented in the hydrosphere over the past century have their origins in human activity.

Near Earth's surface, precipitation of water out of the atmosphere occurs mostly in the forms of rain and snow. Hail contributes locally when conditions of strong, upward motion and freezing at lower levels of the atmosphere occur within passing thunderstorms and result in the formation of ice balls and lumps. The Northern and Southern Hemisphere monsoons are also precipitation-related phenomena, representing periods of particularly intense rainfall driven by strong, seasonal, wind-induced movements of moisture-laden air off the ocean and onto an adjacent landmass.

At the same time, the patterns of evaporation that recycle water back to the atmosphere are heavily dependent upon both atmospheric and ocean temperature, which themselves vary in dynamic ways. Evaporation and precipitation are key processes that help determine the occurrence of rare meteorological events such as the storm bursts, cyclones, and deluges that feed catastrophic (from the human perspective) flooding; alternatively, the absence of precipitation can lead to equally catastrophic dryings and droughts.

In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC, 2007) paid much attention to the possibility human greenhouse-induced warming would lead to an increase in either or both the number and severity of extreme meteorological events. Subsequently, however, an IPCC expert working group (IPCC, 2012) has determined:

> There is medium evidence and high agreement that long-term trends in normalised losses have not been attributed to natural or anthropogenic climate change. … The statement about the absence of trends in impacts attributable to natural or anthropogenic climate change holds for tropical and extratropical storms and tornados. … The absence of an attributable climate change signal in losses also holds for flood losses.

This chapter, building on the earlier conclusions of Idso and Singer (2009) and Idso *et al.* (2011), updates the Nongovernmental International Panel on Climate Change's (NIPCC) summary of the scientific literature on global warming as it might affect the hydrosphere. We again find changes in evaporation, precipitation, drought, ocean heat, ocean circulation, and sea level occur mostly in ways that contradict and rarely reinforce the claims of the IPCC and the projections of its models. Contrary to what has been feared would be caused by rising carbon dioxide levels, over the past 50 years there have been no CO_2-linked changes in precipitation patterns or river flows; signs exist of deceleration rather than acceleration of sea-level rise; and there have been no unnatural changes in the rate or pattern of Atlantic meridional overturning circulation (MOC).

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6.1 The Hydrosphere

Key Findings

There appears to be nothing unusual about the extremes of wetness and dryness experienced during the twentieth century, or about recent changes in ocean circulation, sea level, or heat content, that would require atmospheric carbon dioxide forcing to be invoked as a causative factor. Natural variability in the frequency or intensity of precipitation extremes and sea-level change occurs largely on decadal and multidecadal time scales, and this variability cannot be discounted as a major cause of recent changes where they have occurred.

The main findings of Section 6.1, The Hydrosphere, are:

- GLOBAL PRECIPITATION. Theoretical climate models indicate atmospheric moisture will be enhanced in a warming world, and therefore global precipitation should have increased in the late twentieth century. Although the empirical evidence is not fully conclusive, it increasingly indicates no temperature-related intensification of the hydrological cycle has occurred recently over the global land surface.

- REGIONAL PRECIPITATION. From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events such as floods and droughts. Regional studies from around the world in general fail to provide evidence of rising or more variable precipitation in the late twentieth century. These studies also show (1) ancient floods or droughts of at least the same magnitude as their modern counterparts occurred repetitively throughout the Holocene (last 10,000 years) and before; (2) decreased rainfall occurred during both climatically warm (Medieval Warm Period) and climatically cool (Little Ice Age) periods; (3) warming is sometimes accompanied by a reduction in precipitation-related weather extremes; (4) no evidence exists for a correlation between precipitation variability and atmospheric levels of CO_2; instead, studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, El Niño-Southern Oscillation, and solar variation implicated as controlling factors.

- WATER RESOURCES. Concern has been expressed that increasing concentrations of atmospheric CO_2 will adversely affect water resources. Nearly all water resource studies show just the opposite occurred during the late twentieth century warming, with moisture becoming more available.

- MONSOONS. Evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. Instead, the data sometimes suggest the opposite and overall suggest precipitation responds mostly to cyclical variations in solar activity. Both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period.

- MONSOON MODELS. Assessments of the predictive skill of monsoon models forced by CO_2 change unanimously find them to be inadequate. If climate models cannot accurately simulate the monsoonal precipitation that affects almost half the world's population, they cannot be relied upon as a basis for setting policy. A better understanding of the role of internal feedback processes as represented by the ENSO, PDO, AMO, solar, and other climatic indices is needed for improved forecasting of monsoon behavior.

- SNOWFALL. Studies from China above 40°N latitude demonstrate late twentieth century warming was accompanied by an increase in winter snow depth, promoting increased vegetative growth in desert areas and grasslands and resulting in a reduction in sand-dust storms. These changes represent environmentally positive developments.

- EVAPORATION. Theoretical considerations suggest late twentieth century warming should have been accompanied by an increase in evaporation. Instead, direct measurements of pan evaporation show a reduction over the twentieth century. This reduction has been linked to reducing insolation (solar dimming) and wind stilling at ground level, caused by increasing cloud cover and atmospheric aerosols.

- DROUGHT. Drought represents moisture deficit, but the relationship between the occurrence of drought and global warming is, at best, weak. In some places severe droughts occurred during the Medieval Warm Period, and in others severe droughts failed to occur during the late twentieth century warming. The evidence suggests the recent warming in particular, and drought in general, are the result of factors other than anthropogenic CO_2 emissions.

- STREAMFLOW. Many authors claim global warming will lead to the intensification of the hydrological cycle and the global occurrence of more floods. Few real-world data support this speculation. Neither global nor regional changes in streamflow can be linked to CO_2 emissions. Moreover, most recent changes in streamflow have been either not deleterious or beneficial—often extremely so. Some studies have identified solar factors or multidecadal cyclicity as more important influences on streamflow variability than is atmospheric CO_2.

6.1.1 Precipitation

All forms of precipitation are dynamic, occurring or not occurring in response to changing atmospheric conditions (especially heat and water vapor) on a minute-by-minute, hourly, daily, weekly, or seasonal basis. Regarding the potential effect of global warming on these patterns, Huntington (2006) has noted there is "a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al.*, 1991; Loaciga *et al.*, 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al.*, 2001).” In reviewing the scientific literature on recent patterns of precipitation, Huntington concluded on a globally averaged basis, precipitation over land had indeed increased by about 2 percent over the period 1900–1998 (Dai *et al.*, 1997; Hulme *et al.*, 1998).

In keeping with this result, model predictions of CO_2-induced global warming often suggest warming should be accompanied by increases in rainfall. For example, Rawlins *et al.* (2006) state, after the *Arctic Climate Impact Assessment* (2005), “warming is predicted to enhance atmospheric moisture storage resulting in increased net precipitation.” Peterson *et al.* (2002) noted “both theoretical arguments and models suggest that net high-latitude precipitation increases in proportion to increases in mean hemispheric temperature,” citing Manabe and Stouffer (1994) and Rahmstorf and Ganopolski (1999). Similarly, Kunkel (2003) says “several studies have argued that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998).” To date, global circulation models (GCMs) have failed to accurately reproduce observed patterns and totals of precipitation (Lebel *et al.*, 2000).

Moise *et al.* (2012) analyzed the changes in tropical Australian climate projected by 19 CMIP3 coupled models for the IPCC’s A2 scenario over the twenty-first century. While equatorial regions to the north of Australia are projected to have increased precipitation during austral summer (December to February) by the end of the twenty-first century, there is no significant change over northern Australia itself, based on the model ensemble mean. There is a large spread in model simulations of precipitation change, with both large positive and negative anomalies. The ensemble mean change in the seasonal cycle of precipitation over tropical Australia is nonetheless small, with precipitation increase during March and April, suggesting a prolonged Australian wet season.

No model consensus exists on how interannual variability of tropical Australian precipitation will change in the future, although more models simulate increased variability than decreased. Correlations between full wet season (October to April) precipitation and austral spring (September to November) NINO 3.4 sea surface temperature anomalies show a slight weakening. The spread in projected precipitation seasonal cycle changes between simulations from the same model is larger than the inter-model range, indicating large internal or natural variability in tropical Australian precipitation relative to the climate change signal. Zonal wind changes indicate an intensification of austral summer low level westerlies combined with a weakening of upper easterlies. Low level westerlies also persist for longer periods of time, consistent with a delay in the monsoon retreat.

All models simulate an increase in the land-ocean temperature contrast in austral summer, with a significant correlation between changes in land-ocean temperature contrast in the pre-monsoon (austral spring) and summer precipitation changes. Analysis of precipitation changes using regime-sorting techniques shows offsetting tendencies from thermodynamic changes associated with enhanced atmospheric moisture and dynamic changes associated with a weakened atmospheric circulation.

Conclusions

We are thus confronted with a dilemma: Although the theoretical expectation, supported by modeling, is that global warming should result in enhanced atmospheric moisture, empirical results often show otherwise. Many scientists are now examining historical precipitation records in an effort to determine how temperature changes of the past have affected Earth’s hydrologic cycle. In the following sections, we review what these studies have revealed about patterns of precipitation, region by region across the globe.

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6.1.1.1. Global

From the human perspective, it is variability and changes to local or regional precipitation that produce the most feared impacts of severe weather events, such as floods and droughts. Nonetheless, some researchers have attempted to address the issue at a global level, as represented by the following studies.

New *et al.* (2001) reviewed several global precipitation datasets and summarized precipitation patterns since the late nineteenth century. They determined precipitation over land fell mostly below the century-long mean over the first 15 years of the record but increased from 1901 to the mid-1950s, remained above the century-long mean until the 1970s, and declined by about the same amount thereafter up to 1992 (taking it well below the century-long mean), before recovering to edge upward towards the century mean. For the entire century there was a slight increase in global land area precipitation, but after 1915 there was essentially no net change.

New *et al.* also studied the oceanic portion of the world between 30°N and 30°S, the precipitation record for which begins in 1920. They found an overall decrease of about 0.3 percent per decade. For the planet as a whole, which is 70 percent covered by water, there probably has been a slight decrease in precipitation since about 1917.

Neng *et al.* (2002) analyzed more recent precipitation data, from 1948 to 2000, to determine the effect of warm ENSO years on annual precipitation over the land area of the globe. Although some regions experienced more rainfall in warm ENSO years, others experienced less. "In warm event years, the land area where the annual rainfall was reduced is far greater than that where the annual rainfall was increased, and the reduction is more significant than the increase." This result conflicts with GCM model projections.

Smith *et al.* (2006) used empirical orthogonal function (EOF) analysis to study annual precipitation variations over 26 years beginning in 1979 using a database from the Global Precipitation Climatology Project (GPCP), which produces a merged satellite and *in situ* global precipitation estimate (Huffman *et al.*, 1997; Adler *et al.*, 2003). The first three EOFs determined accounted for 52 percent of the observed variance in the precipitation data. Mode 1 was associated with mature ENSO conditions and correlated strongly with the Southern Oscillation Index, whereas Mode 2 was associated with the strong warm ENSO episodes of 1982/83 and 1997/98. Mode 3 was uncorrelated with ENSO but associated with changes in interdecadal warming of tropical sea surface temperatures, including increased precipitation over the tropical Pacific and Indian Oceans associated with local ocean warming. This increased precipitation was "balanced by decreased precipitation in other regions," so "the global average change [was] near zero."

Ault *et al.* (2012) summarized the application of GCMs to precipitation analysis, acknowledging "the last generation of models, those comprising [the] Climate Model Intercomparison Project III (CMIP3) archive, was unable to capture key statistics characterizing decadal to multidecadal (D2M) precipitation fluctuations" and "CMIP3 simulations overestimated the magnitude of high frequency fluctuations and consequently underestimated the risk of future decadal-scale droughts.

Ault *et al.* then used the Climate Model Intercomparison Project 5 (CMIP5) network to evaluate the ability of these models to simulate twentieth century variability. Their analyses were conducted using gridded (2.5 x 2.5) version 4 reanalysis product data available from the Global Precipitation Climatology Centre (Rudolf *et al.*, 2005), which spans the period January 1901 through December 2007. They found "CMIP5 simulations of the historical era (1850–2005) underestimate the importance [of] D2M variability in several regions where such behavior is prominent and linked to drought," namely, "northern Africa (e.g., Giannini *et al.*, 2008), Australia (Kiem and Franks, 2004; Verdon *et al.*, 2004; Leblanc *et al.*, 2012), western North America (Seager, 2007; Overpeck and Udall, 2010), and the Amazon (Marengo *et al.*, 2011)."

Ault *et al.* further state "the mismatch between 20th century observations and simulations suggests model projections of the future may not fully represent all sources of D2M variations," noting "if observed estimates of decadal variance are accurate, then the current generation of models depict D2M precipitation fluctuations that are too weak, implying that model hindcasts and predictions may be unable to capture the full magnitude of realizable D2M fluctuations in hydroclimate." As a result, "the risk of prolonged droughts and pluvials in the future may be greater than portrayed by these models."

Sun *et al.* (2012) analyzed monthly precipitation observations from 1940–2009 for the global land surface, having assessed the ocean precipitation data as unreliable for trend analyses. They found a near-zero trend in decadal mean precipitation, a finding consistent with earlier studies that found little variation in global mean precipitation at periods longer than the turnover time for water in the atmosphere (~10 days). They did, however, find a reduction in the global land precipitation variation, such that wet areas became drier and dry areas became wetter. This finding directly contradicts the expectation (Section 6.1.6) that there would be an intensification of the hydrological cycle (i.e., wet areas get wetter and dry areas get drier as stated by Trenberth (2011). Sun *et al.* also found, with respect to monthly precipitation variance (an indicator of extreme precipitation), there was "no relationship to local … or global changes in temperature."

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Earlier Research

Other important studies of rainfall changes, at the regional rather than global level, include the following:

- Stankoviansky (2003) used maps, aerial photographs, field geomorphic investigation, and historical documentation to determine the spatial distribution and history of gully landforms in Myjava Hill Land, Slovakia (near the Czech Republic western border). Stankoviansky found "the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s, and the second between the 1780s and 1840s. Though gullying was caused by the extensive forest clearances undertaken to expand farmland, the triggering mechanism was extreme rainfalls during the Little Ice Age." Stankoviansky concluded "the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age"; he also noted destructive rainfall events were much more common during the Little Ice Age than thereafter "is often regarded as generally valid for Central Europe." In other words, this empirical evidence shows cooling rather than warming results in greater precipitation.
- Giambelluca *et al.* (2008) and Chu *et al.* (2010) undertook assessments of whether warming at a rate of 0.163°C/decade, as experienced recently in Hawaii, was associated with additional rainfall. Five climate change indices for extreme precipitation were calculated from daily observational records between the 1950s and 2007: a simple daily intensity index, the total number of days with precipitation ≥25.4 mm, the annual maximum consecutive five-day precipitation amount, the fraction of annual total precipitation from events that exceeded the 1961–1990 95th percentile, and the number of consecutive dry days. Chu *et al.* documented a change in the types of precipitation intensity since the 1980s, with more frequent light precipitation and less frequent moderate and heavy precipitation, as well as a "shorter annual number of days with intense precipitation and smaller consecutive 5-day precipitation amounts and smaller fraction of annual precipitation due to events

exceeding the 1961–1990 95th percentile in the recent epoch [1980–2007] relative to the first epoch [1950–1979].” IPCC predictions for more precipitation to occur with Hawaiian warming are incorrect; in fact, the opposite occurred.

- Diodato *et al.* (2008) studied erosive rainfall in the Calore River Basin (Southern Italy) using combined data from 425-year-long series of observations (1922–2004) and proxy-based reconstructions (1580–1921). Interdecadal variability was strong, with multidecadal erosional peaks reflecting the behavior of the mixed population of thermo-convective and cyclonic rainstorms that occurred. Like Stankoviansky (2003), they found the “Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall.”
- Xu *et al.* (2008) analyzed 50 years (1957–2006) of upper-air Chinese radiosonde observations, along with parallel surface air temperature and precipitation data. In the summer half of the year, they found, “the Tibetan Plateau acts as a strong ‘dynamic pump’ [that] continuously attracts moist air from the low-latitude oceans.” When reaching the plateau, some of these flows rise along its south side and cause “frequent convections and precipitations,” which feed its mid- and low-latitude glaciers, snow-packs, and lakes, from whence originate many of Asia’s major rivers. This flow system constitutes the largest river runoff from any single location in the world. The Tibetan Plateau has been called the “world’s water tower” because of the strong influence it exerts on northern hemisphere mid-latitude moisture, precipitation, and runoff.

In further analysis of their datasets, the four researchers found recent warming in the plateau started in the early 1970s, and the water vapor content showed an upward trend from the early 1980s and continues to the present time, a pattern similar to that found in the annual precipitation data.

- A longer climate history for the Tibetan Plateau for the past 1,700 years was developed by Zhao *et al.* (2009) based upon carbonate percentages and ostracod abundances in sediment cores from Hurleg Lake in the arid Northeast Tibetan Plateau. They compared those records with a contemporaneous history of precipitation derived from tree-ring analysis and changes in solar activity manifest in solar proxy residual $\Delta^{14}C$ data.

Zhao *et al.* discovered carbonate percentage and ostracod abundance show a consistent pattern with ~200-year moisture oscillations during the past 1,000 years. Cross-spectral analysis between the moisture proxies and solar activity proxy showed high coherence at the ~200-year periodicity. This correlation also is found with Chinese monsoon intensity records and implies the possible solar forcing of moisture oscillations in the NE Tibetan Plateau. In addition, the inverse relationship between the moisture pattern in the Qaidam Basin and tree-ring-based monsoon precipitation in the surrounding mountains suggests “topography may be important in controlling regional moisture patterns as mediated by rising and subsiding air masses in this topographically-complex region.”

- Kim *et al.* (2009) analyzed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006) to assess drought severity using four indices: the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), described as “an intensive measure that considers daily water accumulation with a weighting function for time passage”; a Corrected EDI (CEDI) that “considers the rapid runoff of water resources after heavy rainfall”; an Accumulated EDI (AEDI) that “considers the drought severity and duration of individual drought events”; and a year-accumulated negative EDI (YAEDI) “representing annual drought severity.”

The researchers’ precipitation history and two of their drought severity histories are presented, in that order, in Figures 6.1.1.1.1 and 6.1.1.1.2. It is apparent the only major deviation from long-term normality is the decadal-scale decrease in precipitation and ensuing drought around AD 1900. Neither the last part of the Little Ice Age during the early nineteenth century nor the onset of high carbon dioxide emissions after about 1950 appears to exercise any effect on precipitation or drought in Korea, and similar results are known from around the world.

Conclusions

Although Huntingdon (2006) concluded the evidence on balance was consistent with an ongoing and future intensification of the global hydrological cycle, he acknowledged considerable uncertainties and noted the evidence did not support the likelihood of increasingly frequent and intense tropical storms and floods. Since his review, the evidence remains mixed but increasingly indicates no temperature-related intensification of the hydrological cycle has been observed for the global land surface. Although the data show no global trend indicative of land precipitation intensification, spatial and temporal variations can result in regional trends.

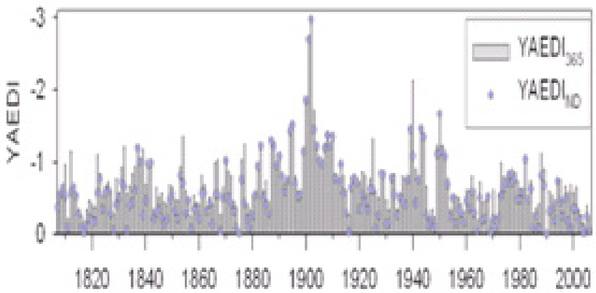

Figure 6.1.1.1.1. Annual "dryness" history at Seoul, Korea, 1807-2006, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

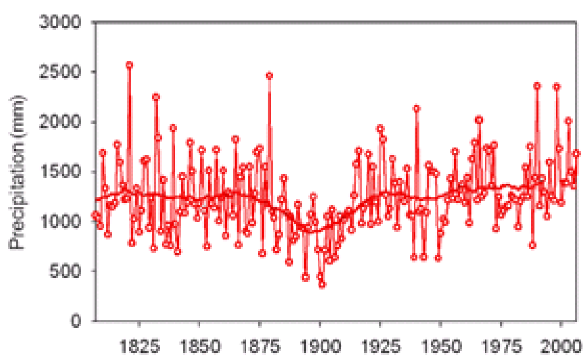

Figure 6.1.1.1.2. Annual precipitation history at Seoul, Korea; solid line, 30-year moving-average. Adapted from Kim *et al.* (2009).

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6.1.1.2. Africa

South Africa has one of the most comprehensive hydro-meteorological databases in the world. Remarkably, 40 years before the establishment of the IPCC, civil engineer D.F. Kokot (1948) published a report for the S.A. Department of Irrigation that found no evidence of a general decrease in the historical records of rainfall or river flow and concluded therefore no link existed between climate change and rainfall over South Africa, a conclusion confirmed by van der Merwe *et al.* (1951).

In the north of Africa another civil engineer, H.E. Hurst, analyzed 1,080 years of flow data from the Nile River for the period 641 to 1946 as part of storage capacity studies for the proposed Aswan High Dam (Hurst, 1951, 1954). He found an unexplained anomaly in the data, also present in other long meteorological (temperature, rainfall) and proxy (lake sediment cores, tree ring) records, which Alexander (1978) identified as related to a 20-year (later, 21-year) periodicity; i.e. to the Hale double sunspot cycle. It thereby became apparent South African periods of flood and drought occurred in a predictable way, rather than occurring at random as had been conventionally believed. The starts of drier and wetter periods are readily identified, characterized by sudden reversals from sequences of years with low rainfall (droughts) to sequences of years with wide-spread rainfall and floods. It is not the simple sum of annual sunspot numbers (Figure 6.1.1.2.1, top graph) that are in synchrony with river flows plotted as the annual departure from the mean (Figure 6.1.1.2.1, fourth graph), but rather the rate of change in sunspot numbers (Figure 6.1.1.2.1, second graph).

Will Alexander, professor of civil engineering at the University of Pretoria, later published several pivotal papers and reports (e.g., Alexander 1995, 2005, 2006; Alexander *et al*., 2004) that greatly increased our understanding of flood-drought cycling in southern Africa and established the importance of solar influence. In his 1995 paper, published just before the end of the severe drought that accompanied cycle G, Alexander predicted the oncoming flood period (G).

Alexander points out nearly all previous analyses of rainfall patterns have been based on the assumption that data for annual rainfall, river flow, and flood peak maxima are independent, identically distributed, and form stationary time series. All three assumptions are wrong.

Detailed, high-quality hydrological datasets from South Africa show instead annual values are sequentially independent but not serially independent; sequential values are not identically distributed as both their mean values as well as their distribution about the mean change from year to year in 21-year sequences; and the series are not stationary in time because of the presence of statistically significant 21-year serial correlation. These properties are related to a synchronous linkage with solar activity, as first reported more than 100 years ago by Hutchins (1889). Later studies by Spate *et al.* (2004) and Whiting *et al.* (2004) also demonstrate flood spate flows in Southern Africa occur on a multidecadal rhythm closely linked to the El Niño-Southern Oscillation.

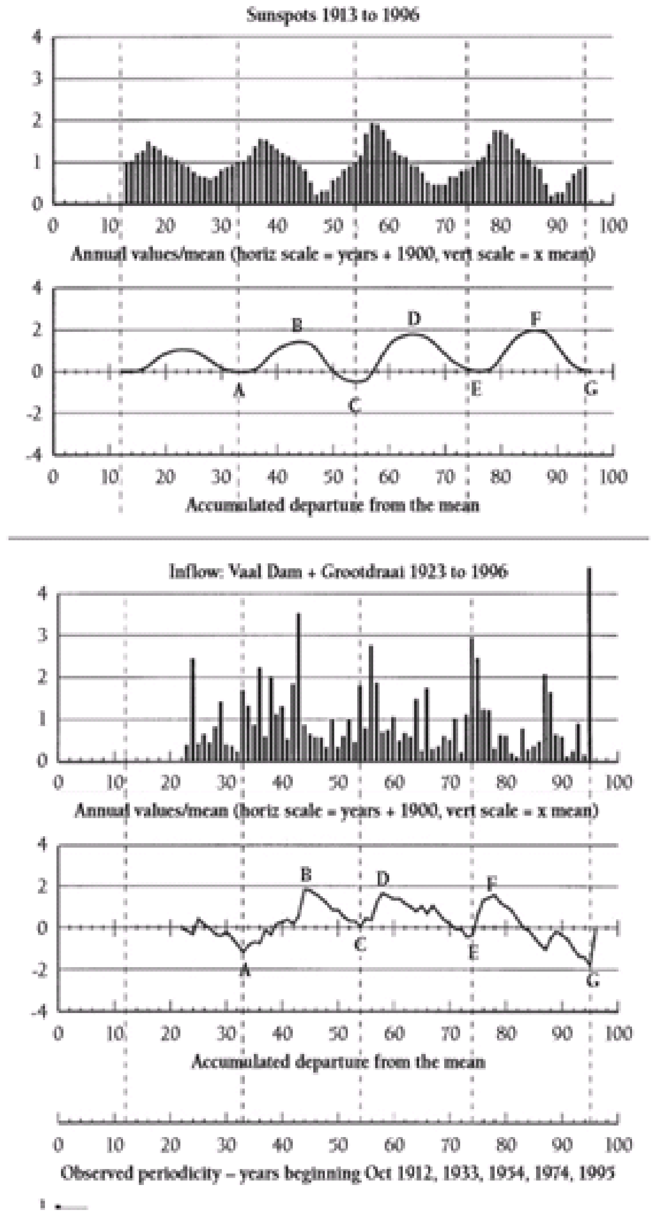

Figure 6.1.1.2.1. Comparison of the characteristics of annual sunspot numbers with corresponding characteristics of annual flows in the Vaal River, South Africa. Adapted from Alexander, W.J.R., Bailey, F., Bredenkamp, D.B., van der Merwe, A., and Willemse, N. 2007. Linkages between solar activity, climate practicability and water resource development. *Journal of the South African Institution of Civil Engineering* **49**: 32–44, Figure 7.

Conclusions

Alexander *et al.* (2007) explain the significance of this pivotal research:

> It is extremely important that all those involved with water resource studies should appreciate that there are fundamental flaws in current global climate models used for climate change applications. These models fail to accommodate the statistically significant, multiyear periodicity in the rainfall and river flow data observed and reported by South African scientists and engineers for more than the past 100 years. They also failed to predict the recent climate reversals based on Alexander's model (Alexander 1995, 2005). The global climate model outputs can therefore not be used for adaptation studies.

Koutsoyiannis (2013) has argued the multiscale change in flow records in the Nile, first recorded by

Hurst and then further analyzed by Alexander and others, indicates long-term flow changes relevant to water engineering are much more frequent and intense than commonly perceived. Accordingly, future system states are much less certain and predictable on long time scales than is implied by standard methods of statistical analysis. From Koutsoyiannis argues a change of perspective is needed, in which change and uncertainty form essential parts of future hydrological analyses.

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Earlier Research

Other significant recent papers on African precipitation patterns include the following:

- In two contextual studies, Lee-Thorp *et al.* (2001) described repeated rapid climate shifts in Southern Africa since the middle Holocene, and Verschuren *et al*. (2000) examined hydrologic conditions in equatorial East Africa over the past one thousand years. Verschuren *et al.* report the region was significantly drier than today during the Medieval Warm Period (AD 1000–1270) and relatively wetter than today during the Little Ice Age (AD 1270–1850). The LIA wetting was interrupted by three episodes of drought in 1390–1420, 1560–1625, and 1760–1840, which were "more severe than any recorded drought of the twentieth century."
- The late eighteenth/early nineteenth century dry period in East Africa also was identified in West Africa by Nicholson (2001). She reports the most significant climatic change over the past 200 years has been "a long-term reduction in rainfall in the semi-arid regions of West Africa," by as much as 20 to 40 percent in parts of the Sahel. There have been, she says, "three decades of protracted aridity" and "nearly all of Africa has been affected ... particularly since the 1980s." Nicholson further notes dry conditions similar to those that have affected nearly all of Africa since the 1980s are not unprecedented; "a similar dry episode prevailed during most of the first half of the 19th century."
- Nicholson and Yin (2001) report there have been two starkly contrasting climatic episodes in equatorial East Africa since the late 1700s. The first, which began prior to 1800, was characterized by "drought and desiccation." Extremely low lake levels were the norm as drought reached its extreme during the 1820s and 1830s. In the mid to latter part of the 1800s, the drought began to weaken and floods became "continually high." By the turn of the century, lake levels began to fall as mild drought conditions returned. The drought did not last long, and the latter half of the twentieth century has seen an enhanced hydrologic cycle with a return of some lake levels to the high stands of the mid to late 1800s.
- Richard *et al*. (2001) analyzed summer (January-March) rainfall totals in southern Africa over the

period 1900–1998, finding interannual variability was higher for the periods 1900–1933 and 1970–1998 but lower for the period 1934–1969. The strongest rainfall anomalies (greater than two standard deviations) were observed at the beginning of the century. The authors conclude there were no significant changes in the January-March rainfall totals nor any evidence of abrupt shifts during the twentieth century.

Conclusions

Three conclusions can be drawn from the African rainfall data.

- The recent much-commented recent drying in the Sahel is not in itself evidence of human-caused warming, because similar dry periods occurred periodically during the recent past.

- There is no established relationship between rainfall trends or changes in Africa and increased atmospheric carbon dioxide during the second half of the twentieth century.

- Contrary to some climate model projections, decreased rainfall can occur during both climatically warm (MWP) and climatically cool (LIA) times.

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6.1.1.3. Mediterranean

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Mediterranean region include the following:

- Rodrigo *et al.* (2000, 2001) reconstructed a seasonal rainfall record for 1501–1997 for Andalusia (southern Spain), and established a relationship exists with the North Atlantic Oscillation (NAO) over the period 1851–1997. Their research established the NAO index correlation with climate is strongest in winter, when it explains 40 percent of the total variance in precipitation. Rodrigo *et al.* stress "the recent positive temperature anomalies over western Europe and recent dry winter conditions over southern Europe and the Mediterranean are strongly related to the persistent and exceptionally strong positive phase of the NAO index since the early 1980s," as opposed to an intensification of global warming.
- Crisci *et al.* (2002) analyzed rainfall data from 81 gauges throughout Tuscany (central Italy) for three periods: from the beginning of each record through 1994; a shorter 1951–1994 period; and a still-shorter 1970–1994 period. For each of these periods, trends were derived for extreme rainfall durations of 1, 3, 6, 12, and 24 hours.

For the period 1970–1994, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested. For the longer 1951–1994 period, the majority of all stations exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations and one had negative trends at all durations. For the still-longer complete period of record, the majority of all stations again exhibited no trends in extreme rainfall at any of the durations tested; none had positive trends at all durations, and one had negative trends at all durations. Such global warming as may have occurred during the twentieth century clearly had no impact on Italian rainfall.

- Tomozeiu *et al.* (2002) performed a series statistical tests to investigate the nature and potential causes of trends in winter (December–February) mean precipitation recorded at 40 stations in Northern Italy over the period 1960–1995. Nearly all stations experienced significant decreases in winter precipitation over the 35-year period of study, and a Pettitt test indicated a significant downward shift at all stations around 1985. An Empirical Orthogonal Function analysis revealed a principal component representing the North Atlantic Oscillation (NAO), as found also by Rodrigo *et al.* (2001), suggesting the changes in winter precipitation around 1985 "could be due to an intensification of the positive phase of the NAO."

- Sousa and Garcia-Murillo (2003) studied proxy indicators of climatic change, including precipitation, in Doñana Natural Park in Andalusia (southern Spain) for a period of several hundred years and compared their results with those of other researchers. The work revealed the Little Ice Age (LIA) was non-uniform and included periods both wetter and drier than average. Nevertheless, they cite Rodrigo *et al.* (2000) as indicating "the LIA was characterized in the southern Iberian Peninsula by increased rainfall" and Grove (2001) as indicating "climatic conditions inducing the LIA glacier advances [of Northern Europe] were also responsible for an increase in flooding frequency and sedimentation in Mediterranean Europe." Sousa and Garcia-Murillo's research complements the others' work, finding "an aridization of the climatic conditions after the last peak of the LIA (1830–1870)," suggesting much of Europe became drier, not wetter, as Earth passed out of the Little Ice Age.
- Alexandrov *et al.* (2004) analyzed a number of twentieth century datasets from throughout Bulgaria and found "a decreasing trend in annual and especially summer precipitation from the end of the 1970s"; they note "variations of annual precipitation in Bulgaria showed an overall decrease." In addition, the region stretching from the Mediterranean into European Russia and the Ukraine "has experienced decreases in precipitation by as much as 20% in some areas."
- Touchan *et al.* (2005) used tree-ring data to develop summer (May–August) precipitation reconstructions for eastern Mediterranea (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back as much as 600 years. The research showed summer precipitation varied on multiannual and decadal timescales but without any overall long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods in 1601–1605 and 1751–1755. Both extreme wet and dry precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930.
- Clarke and Rendell (2006) analyzed 50 years of rainfall records (1951–2000) from eastern Basilicata (southern Italy) and compared them with the occurrence of floods and landslides. They found "the frequency of extreme rainfall events in this area declined by more than 50% in the 1990s compared to the 1950s." In addition, the "impact frequency also decreased, with landslide-event frequency changing from 1.6/year in the period 1955–1962 to 0.3/year from 1985 to 2005, while flood frequency peaked at 1.0/year in the late 1970s before declining to less than 0.2/year from 1990." If the climate-driven changes that occurred over the latter part of the twentieth century continue, Clarke and Rendell conclude, "the landscape of southern Italy and the west-central Mediterranean will become increasingly stable."

Conclusions

Several studies from the Mediterranean region show summer precipitation in the eastern Mediterranean became less variable as late twentieth century warming occurred than it had been in the earlier part of the century or in previous centuries. None of the Mediterranean studies provides evidence for the rising or more variable precipitation in the late twentieth century predicted by global climate models.

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6.1.1.4 Central Europe

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Central Europe include the following:

- Koning and Franses (2005) analyzed a century of daily precipitation data for the Netherlands, acquired at the de Bilt meteorological station in Utrecht. Using robust nonparametric techniques, they found the cumulative distribution function of annual maximum precipitation levels of rainfall remained constant throughout the period 1906–2002, leading them to conclude "precipitation levels are not getting higher." The authors also report similar analyses performed for the Netherlands' five other standard meteorological stations "did not find qualitatively different results."
- Wilson *et al.* (2005) developed two March–August precipitation chronologies for the Bavarian Forest of southeast Germany, based on tree-ring widths obtained for the period 1456–2001. The first chronology, standardized with a fixed 80-year spline function (SPL), was designed to retain decadal and higher frequency variations; the second used regional curve standardization (RCS) to retain lower frequency variations. The SPL chronology failed to reveal any significant yearly or decadal variability, and there did not appear to be any trend toward either wetter or drier conditions over the 500-year period. The RCS reconstruction, by contrast, capturing lower frequency variation better, showed March–August precipitation was substantially greater than the long-term average during the periods 1730–1810 and 1870–2000 and less than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870. The found little evidence of a long-term trend, however, or of any relationship to accumulating CO_2 emissions.
- Solomina *et al.* (2005) derived the first spring (April–July) tree-ring reconstruction for the period 1620–2002 for the Crimea Peninsula (Ukraine). This chronology was correlated with an earlier precipitation reconstruction derived from a sediment core taken in 1931 from nearby Saki Lake, providing a proxy precipitation record for the region that stretches back 1,500 years to AD 500. A parallel instrumental record from near the tree-sampling site shows no trend in precipitation over about the past century (1896–1988).

  The reconstructed precipitation values from the tree-ring series revealed year-to-year and decadal variability but were near-average with relatively few extreme values between about the middle 1700s and the early 1800s, and again since about 1920. The most notable anomaly of the 1,500-year reconstruction was an "extremely wet" period between AD 1050 and 1250, which Solomina *et al.* describe as broadly coinciding with the Medieval Warm Period, when humidity was higher than during the instrumental era.
- Zanchettin *et al.* (2008) demonstrated rainfall variability across Europe is influenced by the interaction of NAO, ENSO, and the PDO. Multidecadal variability in these indices may produce nonstationary rainfall variability on multidecadal timescales.

Conclusions

These studies demonstrate enhanced precipitation did not occur in Central Europe during the twentieth century global warming.

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6.1.1.5. Boreal

Earlier Research

Earlier Boreal research concerning the relationship between precipitation and climate change include the following papers:

- Hanna *et al.* (2004) analyzed variations in several climatic variables in Iceland over the past century, including precipitation. For the period 1923–2002, precipitation appeared to have increased slightly, although they question the veracity of the trend citing several biases that may have corrupted the data base.
- Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June–August) precipitation in east central Sweden. This work revealed a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record. Over the past century of supposedly unprecedented global warming, however, precipitation was found to have exhibited less variability than it did during the preceding 150 years.
- Linderholm and Chen (2005) derived a 500-year winter (September–April) precipitation chronology using tree-ring data obtained from the forest zone of west-central Scandinavia. Their record exhibited considerable variability except for a fairly stable period of above-average precipitation between AD 1730 and 1790. Above-average winter precipitation also was found to have occurred in 1520–1561, 1626–1647, 1670–1695, 1732–1851, 1872–1892, and 1959 to the present, with the highest values reported in the early to mid-1500s. Below-average winter precipitation was observed during 1504–1520, 1562–1625, 1648–1669, 1696–1731, 1852–1871, and 1893–1958, with the lowest values occurring at the beginning of the record and the beginning of the seventeenth century.

Conclusions

These findings demonstrate conditions irregularly alternating between wetter and drier than the present have occurred repeatedly within the Boreal region throughout the past five centuries, with no particular sign of an additional influence from carbon dioxide emissions in the late twentieth century. Similar conditions can be expected to recur naturally in the future.

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6.1.1.6. Arctic

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in the Arctic region include the following:

- Curtis *et al.* (1998) examined a number of climatic variables at two first-order Arctic weather stations (Barrow and Barter Island, Alaska) from records that began in 1949. Both the frequency and mean intensity of precipitation decreased at these stations over the period of record. Though temperatures in the western Arctic increased over this period, "the observed mean increase varies strongly from month-to-month making it difficult to explain the annual trend solely on the basis of an anthropogenic effect resulting from the increase in greenhouse gases in the atmosphere." The four researchers conclude the theoretical model-based assumption that "increased temperature leads to high precipitation ... is not valid," at least for the part of the western Arctic that was the focus of their study.
- Lamoureux (2000) analyzed varved sediments from Nicolay Lake, Cornwall Island, Nunavut, Canada, comparing them with rainfall events recorded at a nearby weather station over the period 1948–1978. A rainfall history was established for the region over the 487-year period 1500–1987. The record was suggestive of a small, statistically insignificant increase in rainfall over the period. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic as well as the Arctic as a whole. Lamoureux also found "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic

types during the coldest periods of the Little Ice Age."

- Rawlins *et al.* (2006) calculated trends in the averaged water equivalent of annual rainfall and snowfall for 1936–1999 across the six largest Eurasian drainage basins that feed major rivers delivering water to the Arctic Ocean. The annual rainfall across the total area of the six basins decreased consistently and significantly over the 64-year period. Annual snowfall, by contrast, underwent a strongly significant increase until the late 1950s. Thereafter, snowfall declined, and "no significant change [was] determined in Eurasian-basin snowfall over the entire 64-year period." Overall, annual total precipitation (rainfall and snowfall) decreased over the period of this study. The authors report their finding is "consistent with the reported (Berezovskaya *et al.*, 2004) decline in total precipitation."

Conclusions

These studies, and especially that of Lamoureux (2000), show the late twentieth century warming was accompanied by a *reduction* in the number of weather extremes related to precipitation in a part of the planet predicted to be most affected by CO_2-induced global warming, the Canadian High Arctic.

Thus we can conclude either the theoretical arguments and model predictions that suggest "high-latitude precipitation increases in proportion to increases in mean hemispheric temperature" are not robust; or late twentieth century temperatures were not warmer than those of the mid-1930s and '40s; or both of the above. All three conclusions fail to provide support for a key claim of the *Arctic Climate Impact Assessment* (2005).

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6.1.1.7. United States

For the most part, droughts in the United States have become shorter, less frequent, and less severe over the past century, and they have covered smaller areas (Figure 6.1.1.7.1).

Chen *et al.* (2012) set out to test the prediction that an increase in air temperature would result in higher evapotranspiration, thereby reducing available water and causing drought (IPCC, 2007; Karl *et al.*, 2009). Though the basis for the prediction is unsound, the test nonetheless revealed important results about the standard precipitation index (SPI) in relation to drought intensity for the Southern United States for 1895–2007. Chen *et al.* found "no obvious increases in drought duration and intensity during 1895–2007" and "no obvious increase in air temperature for the entire SUS during 1895–2007."

Conclusions

Once again, predictions made by the IPCC (2007) and the authors of the U.S. climate report of 2009 (Karl *et*

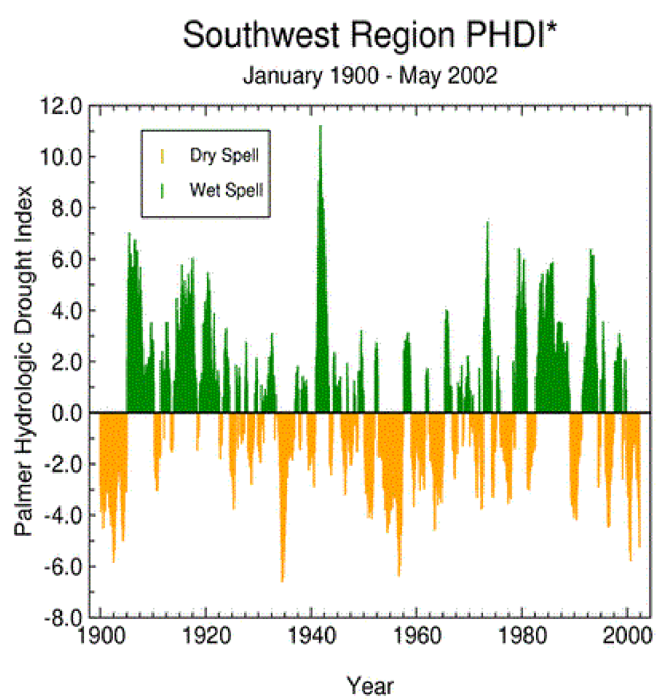

Figure 6.1.1.7.1. Drought Index for the southwestern US, 1900–2002. National Climatic Data Center, National Environmental Satellite, Data, and Information Service, National Oceanographic and Atmospheric Administration, http://www.ncdc.noaa.gov/sotc/drought/2002/5#paleo.

al., 2009), who warn of intensification of the hydrological cycle with increasing severity of extremes, are found to be without any confirmation in pertinent real-world data.

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Earlier Research

Earlier U.S. hydrological studies with respect to global warming include the following papers.

- Haston and Michaelsen (1997) used proxy tree-ring data to develop a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border. Although regionwide precipitation during the twentieth century was higher than during the preceding three centuries, they found, it also was “less variable compared to other periods in the past.” However, Pierce *et al.* (2013) reviewed the results of 25 model projections of precipitation changes for California by 2060. They found 12 projected drier conditions and 13 projected wetter conditions, concluding California was likely to become drier, in contrast to the weak trend reported by Haston and Michaelsen.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. They detected a significant increasing trend in annual precipitation in the basin, driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range; at the same time, essentially no change occurred at the high-intensity end of the spectrum. For streamflow, no trend occurred at the annual timescale but monthly totals increased in low-flow months and decreased in high-flow months. No correlation exists between those changes and the CO_2 content of the atmosphere.
- Cronin *et al.* (2000) analyzed salinity gradients in sediment cores from Chesapeake Bay, the largest estuary in the United Sates, to determine precipitation variability in the surrounding watershed over the past 1,000 years. The authors identified a high degree of decadal and multidecadal variability between wet and dry conditions throughout the record, with inferred regional precipitation fluctuating by between 25 and 30 percent, often in “extremely rapid [shifts] occurring over about a decade.” Precipitation over the past two centuries was on average greater than during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the climate was judged to have been “extremely wet.” The researchers also determined this region, like the southwestern United States, had experienced several “mega-droughts” lasting from 60 to 70 years, some being “more severe than twentieth century droughts.”
- Cowles *et al.* (2002) analyzed snow-water equivalent (SWE) data for 1910–1988 obtained at more than 2,000 sites in the western United States using four measuring systems—snow courses, snow telemetry, aerial markers, and airborne gamma radiation. Though the whole-area trend in SWE was negative, significant differences from trend occurred in the southern Rocky Mountains where no change occurred with time. Cowles *et al.* note their results “reinforce more tenuous conclusions made by previous authors,” citing Changnon *et al.* (1993) and McCabe and Legates (1995), who studied snowpack data from 1951–1985 and 1948–1987, respectively, at 275 and 311 sites. They too found a decreasing trend in SWE at most sites in the Pacific Northwest but more ambiguity in the southern Rockies.
- Garbrecht and Rossel (2002) used state divisional monthly precipitation data from the U.S. National Climatic Data Center to investigate precipitation on the Great Plains from January 1895 through December 1999. The authors found regions in the central and southern Great Plains experienced above-average precipitation over the past two decades of the twentieth century, and this 20-year period marked the longest and most intense wet interval of the 105 years of record. The enhanced precipitation resulted primarily from a reduction in the number of dry years and an increase in the number of wet years. The number of very wet years did not increase as much and showed a decrease for many regions. The northern and northwestern Great Plains also

experienced a precipitation increase at the end of this 105-year interval, but it was primarily confined to the final decade of the twentieth century and again was marked by the occurrence of fewer dry years, not increased wet ones.

- McCabe and Wolock (2002) evaluated precipitation trends for the conterminous United States for 1895–1999. They considered annual precipitation minus annual potential evapotranspiration (net precipitation), surplus water that eventually becomes streamflow, and any water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. For the United States as a whole, they found a statistically significant increase in the first two of these three parameters, while for the third there was no change.
- Kunkel *et al.* (2003) also studied the conterminous United States, using a new database of daily precipitation observations for the period 1895–2000. The new data indicated heavy precipitation occurred more commonly during the late nineteenth and early twentieth centuries, decreased to a minimum in the 1920s and 1930s, and then increased into the 1990s. Kunkel *et al.* note "for 1-day duration events, frequencies during 1895–1905 are comparable in magnitude to frequencies in the 1980s and 1990s" and "for 5- and 10-day duration events, frequencies during 1895–1905 are only slightly smaller than late 20th century values."
- Ni *et al.* (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico using a network of 19 tree-ring chronologies. With respect to drought, they found "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570–97, 1664–70, the 1740s, the 1770s, and the late 1800s." They also note the 1950s drought "was large in scale and severity, but it only lasted from approximately 1950 to 1956," whereas the sixteenth century megadrought lasted more than four times as long. With respect to rainfall, Ni *et al.* report several wet periods comparable to the wet conditions seen in the early 1900s and after 1976 occurred in "1108–20, 1195–1204, 1330–45, the 1610s, and the early 1800s." They also note "the most persistent and extreme wet interval occurred in the 1330s."

Regarding the causes of the precipitation extremes, Ni *et al.* state "the 1950s drought corresponds to La Niña/-PDO [Pacific Decadal Oscillation] and the opposite polarity [+PDO] corresponds to the post-1976 wet period." This led them to hypothesize that the prominent shifts seen in the 1,000-year precipitation reconstructions from Arizona and New Mexico may be linked to strong shifts in the coupled ENSO-PDO system.

- Using collated paleo-data, Verdon and Franks (2006) demonstrated PDO phases are significantly associated with changes in the frequency of both warm and cold ENSO events. This multidecadal variability of event frequency has marked implications for secular trends in U.S. climate, as also discovered by Ni *et al.* (2002).
- Gray *et al.* (2003) examined 15 tree-ring-width series used in previous reconstructions of drought for evidence of low-frequency variation in precipitation in five regions of the central and southern Rocky Mountains. They identified strong multidecadal phasing of moisture variation in all regions, a late sixteenth century megadrought, and showed "oscillatory modes in the 30–70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." Like Ni *et al.* (2002), they note these changes "may ensue from coupling of the cold phase PDO [Pacific Decadal Oscillation] with the warm phase AMO [Atlantic Multidecadal Oscillation] (Cayan *et al.*, 1998; Barlow *et al.*, 2001; Enfield *et al.*, 2001)," something they envision happened in both the severe drought of the 1950s and the late sixteenth century megadrought.

Conclusions

Nearly all climate models suggest the planet's hydrologic cycle will be enhanced in a warming world and that precipitation should therefore have increased in the late twentieth century. This prediction is especially applicable to the Pacific Northwest of the United States, where Kusnierczyk and Ettl (2002) report climate models predict "increasingly warm and wet winters," as do Leung and Wigmosta (1999). As Cowles *et al.* (2002) show clearly, however, precipitation that fell and accumulated as snow in the western U.S. and Pacific Northwest during the late twentieth century was in fact reduced, not enhanced (see Figure 6.1.1.7.2).

Other studies show great variability in periods of wet and drought over a climatic time scale, with the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, and El Niño-Southern Oscillation implicated as controlling factors.

Thus there appears to be nothing unusual about the extremes of wetness and dryness experienced

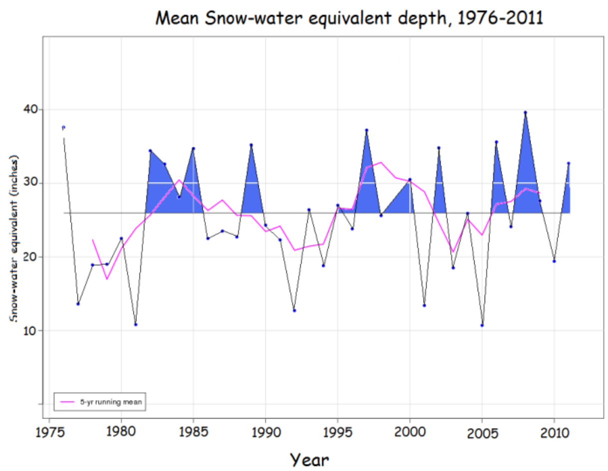

Figure 6.1.1.7.2. Mean snow accumulation in western USA, 1975-2011 (US National Resources Conservation Service, SNOTEL).

during the twentieth century that requires atmospheric CO_2 forcing to be invoked as a causative factor. In particular, several studies show frequencies of extreme precipitation events in the United States in the late 1800s and early 1900s were about as high as in the 1980s and 1990s. Natural variability in the frequency of precipitation extremes is large on decadal and multidecadal time scales and cannot be discounted as the cause or one of the causes of recent increases in precipitation where they have occurred.

Cronin *et al.*'s (2002) work, like the study of Ni *et al.* (2002), reveals nothing unusual about precipitation in the United States during the twentieth century, the last two decades of which the IPCC claims were the warmest of the past two millennia. Cronin *et al.*'s work indicates, for example, both wetter and drier intervals occurred repeatedly in the past in the Chesapeake Bay watershed. There is reason to believe such intervals will occur in the future with or without any further global warming.

Great concern has been expressed that increasing concentrations of carbon dioxide in the atmosphere will cause global warming that will in turn adversely affect water resources. The results of nearly all available U.S. studies reveal that during the twentieth century warming just the opposite has occurred: Moisture has become more available, and there has been no change in the amount of water required for optimum plant growth.

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6.1.1.8. Canada and Mexico

Earlier Research

Papers that have addressed the relationship between precipitation and climate change in Canada and Mexico include the following:

- Lamoureux (2000) analyzed varved lake sediments from Nicolay Lake, Cornwall Island, Nunavut (Canada), comparing the resulting climate history with the 1948–1978 rainfall history recorded at a nearby weather station. This enabled the construction of a rainfall history for the 487-year period between 1500 and 1987. No statistically significant increase in total rainfall was found to have occurred over period studied. Heavy rainfall was most frequent during the seventeenth and nineteenth centuries, the coldest periods of the past 400 years in the Canadian High Arctic and the Arctic as a whole. In addition, Lamoureux states, "more frequent extremes and increased variance in yield occurred during the 17th and 19th centuries, likely due to increased occurrences of cool, wet synoptic types during the coldest periods of the Little Ice Age."
- Zhang *et al.* (2001) also studied the history of heavy precipitation events across Canada, using "the most homogeneous long-term dataset currently available for Canadian daily precipitation." No significant long-term trends were apparent in the data, and decadal-scale variability was the dominant feature of both the frequency and intensity of the annual extreme precipitation events. Seasonal data, however, revealed an increasing trend in the number of extreme autumn snowfall events and precipitation totals (extreme plus non-extreme events) revealed a slightly increasing trend due to increases in the number of non-heavy precipitation events. Zhang *et al.* concluded "increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada."
- Diaz *et al.* (2002) created a 346-year history of winter-spring (November–April) precipitation for the Mexican state of Chihuahua, south of the U.S., using earlywood tree-ring width chronologies from more than 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua's northeast border. Diaz *et al.* found "three of the five worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century." Two of those three worst drought years occurred during a decadal period of average to slightly above-average precipitation, so the three years were not representative of long-term droughty conditions. The longest drought lasted 17 years (1948–1964), but for several of the years of that interval, precipitation values were only slightly below normal. Four very similar dry periods were interspersed throughout the preceding two-and-a-half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s. Considering the twentieth century alone, a long period of high winter-spring precipitation stretched from 1905 to 1932 and, following the major drought of the 1950s, precip-itation remained at or just slightly above normal for the remainder of the record.

No long-term trend is apparent over the full 346 years of record, nor is there any evidence of a significant departure from no-trend over the twentieth century. Consequently, and despite the spasmodic drought events described above, Chihuahua's precipitation history did not differ significantly during the twentieth century from what it was over the prior quarter of a millennium.

- The IPCC predicts global warming will produce an increase in heavy precipitation. Kunkel (2003) looked for such a signal in precipitation data from Canada covering much of the last century but found "no discernible trend in the frequency of the most extreme [precipitation] events in Canada."

Conclusions

Rainfall records from Canada and Mexico provide no support for the claim that increasing greenhouse gas concentrations will result in an increase of heavy precipitation (Cubasch *et al.*, 2001; Yonetani and Gordon, 2001; Kharin and Zwiers, 2000; Zwiers and Kharin, 1998; Trenberth, 1998). Neither a long-term trend nor a late twentieth century trend of increasing precipitation is apparent in most records, which are instead dominated mainly decadal variability.

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6.1.2. Monsoons

Monsoonal climates bring abundant seasonal rainfall in Asia, northern Australia, South America, and South Africa. The Asian monsoon alone is said to influence nearly half of the world's population, people whose agriculture, way of life, and society all depend on the regularity of the summer monsoon.

A particularly useful perspective on monsoonal variation in climatic context is provided by Vuille *et al.*'s (2012) study of the South American monsoon, which builds on earlier research by Bird *et al.* (2011). These authors use proxy records derived from speleothems, ice cores, and lake sediments from the tropical Andes and Southeast Brazil to reconstruct a history of the monsoon system over the past two thousand years. They report very coherent monsoonal behavior over the past two millennia, in which decadal to multidecadal variability is superimposed on large climatic excursions that occurred during the Medieval Warm Period, Little Ice Age, and late twentieth century warm period. Monsoonal strengthening occurred during the LIA and weakening during the two warm periods. Vuille *et al.* conclude the longer scale climate anomalies "were at least partially driven by temperature changes in the Northern Hemisphere and in particular over the North Atlantic, leading to a latitudinal displacement of the Intertropical Convergence Zone and a change in monsoon intensity (amount of rainfall upstream over the Amazon Basin)."

Li *et al.* (2012) also provide context for changes in monsoonal activity, developing a summer surface salinity reconstruction for the past millennium from the Southern Okinawa Trough, East China Sea, based on a high-resolution diatom record. They found high-salinity conditions generally prevailed during the Medieval Warm Period (905–1450 AD), whereas the Little Ice Age was characterized by relatively low-salinity conditions, perhaps caused by increased freshwater discharge from Taiwan's Lanyang River.

The East Asian monsoon is a highly active and important part of the global climate system, with heavy summer monsoonal precipitation causing large discharges of freshwater into the southeastern East China Sea, variability in which has been documented from speleothem records (Wang *et al.*, 2001, 2008;

Partin *et al.*, 2007; Chang *et al.*, 2009). The report by Li *et al.* of increased China Sea region monsoonal activity during the Medieval Warm Period, and its reduction during the Little Ice Age, based on marine salinity variations, is an important confirmation of earlier land-based studies.

Bombardi and Carvalho (2009) evaluated the ability of ten IPCC global coupled climate models, each with distinct physics and resolution, to simulate characteristics of the modern South American Monsoon System (SAMS). Model outputs were compared with data for the onset, end, and total rainfall of SAMS, as characterized by precipitation data for the period 1979–2006 derived from the Global Precipitation Climatology Project.

Bombardi and Carvalho found the annual precipitation cycle for SAMS "is poorly represented by most models"; for example, "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." Most models, they note, "tend to underestimate precipitation during the peak of the rainy season." The authors attribute the failure of the modeling to "the misrepresentation of the Inter-Tropical Convergence Zone and its seasonal cycle," noting also, "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon."

In a similar study, Zhang *et al.* (2012) assessed the efficacy of GCM models to project variability and changes in the Asian monsoon. They used daily precipitable water and 850 hPa monsoon wind data to analyze potential changes in Asian monsoon onset, retreat, and duration, as simulated by 13 IPCC AR4 models. They report no model stands out as better than the 12 others and some models show "significant biases in mean onset/retreat dates and some failed to produce the broad features of how [the] monsoon evolves." Flagrant contradictions occur between different groups of models. Over Asian land, for example, the 13 models "are nearly equally divided about the sign of potential changes of onset/retreat." Zhang *et al.* concede they "do not know why the models are different in simulating these dominant processes and why in some models the ENSO influence is more significant than others." They acknowledge also, as already found by Solomon *et al.* (2007) and Wang *et al.* (2009), that it is "unclear what are the key parameterizations leading to the differences in simulating ENSO and its responses to global warming." In an important but little-cited statement, Zhang *et al.* conclude "there is a long way ahead before we can make skillful and reliable prediction of monsoon onset, duration, intensity and evolution in [a] warmed climate."

Kim *et al.* (2012) studied the Asian monsoon using retrospective predictions (1982–2009) from the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) seasonal prediction systems. Both the SYS4 and CFSv2 models exhibited a cold bias in sea-surface temperature (SST) compared with observations over the Equatorial Pacific, North Atlantic, Indian Oceans, and a broad region in the Southern Hemisphere and a warm bias over the northern part of the North Pacific and North Atlantic Oceans. Additionally, the models predict excessive precipitation along the Intertropical Convergence Zone, equatorial Atlantic, equatorial Indian Ocean, and the maritime continent. The researchers found the southwest monsoon flow and Somali Jet are stronger in SYS4, while the southeasterly trade winds over the tropical Indian Ocean, the Somali Jet, and the Subtropical northwestern Pacific high are weaker in CFSv2 relative to the reanalysis.

Wang *et al.* (2013) investigated the decadal variability of the Northern Hemisphere summer monsoon. They found the variability observed since the 1970s was associated with an intensification of Hadley and Walker circulation, contradicting theoretical predictions and numerical model projections. They propose an alternative index, the mega-El Niño/Southern Oscillation, which combined with the AMO provides a good predictor of monsoon intensity. Their analysis shows the importance of internal feedback processes and displays a poor correspondence with global warming, although Wang *et al.* suggest it is consistent with projections of a warm Northern Hemisphere-cold Southern Hemisphere due to greenhouse gas forcing, due to an increased thermal gradient between the hemispheres based on the ERA-40 and ERAI reanalysis datasets.

Conclusions

The reports by Vuill *et al.* (2012) and Li *et al.* (2012) show both the South American and Asian monsoons became more active during the cold Little Ice Age and less active during the Medieval Warm Period. Moreover, Bombardi and Carvalho (2009), Zhang *et al.* (2012), and Kim *et al.* (2012) unanimously conclude the predictive skill of monsoon models is inadequate. If the climate modeling enterprise cannot simulate the monsoonal precipitation that affects almost half the world's population, climate GCMs cannot be anywhere near good enough to be relied on as a basis for setting policy.

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Earlier Research

Many other important papers have been published on the topic of the monsoon from the Middle East and across central Asia to Japan, including these:

- Pederson *et al.* (2001) used tree-ring chronologies from northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Analyses of standard deviations and five-year intervals of extreme wet and dry periods for this record revealed "variations over the recent period of instrumental data are not unusual relative to the prior record." Though more frequent extended wet periods have occurred in recent decades, this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models," they write. Spectral analysis of the data reveals significant periodicities around 12 and 20–24 years, possibly "evidence for solar influences in these reconstructions for northeastern Mongolia."
- Neff *et al.* (2001) considered a ^{14}C growth-ring record and a $\delta^{18}O$ proxy record of monsoon rainfall intensity from an early Holocene (9,600–6,100 yBP) speleothem from northern Oman. Correlation between the two datasets was "extremely strong" and a spectral analysis of the data revealed statistically significant periodicities centered on 779, 205, 134, and 87 years for the $\delta^{18}O$ record, and periodicities of 206, 148, 126, 89, 26, and 10.4 years for the ^{14}C record. Because variations in ^{14}C are generally attributed to variations in solar activity and the ^{14}C record correlated strong with the $\delta^{18}O$ record, and because their spectral analyses supported that correlation, Neff *et al.* conclude there is "solid evidence" that both signals stem from solar forcing.
- Kripalani *et al.* (2003) set out to test IPCC predictions of increased variability and strength of the

Asian monsoon under a global warming regime. The authors examined Indian monsoon rainfall for 1871–2001 using data obtained from 306 stations distributed across the country. The rainfall records display distinctive, three decade-long, alternating epochs of above- and below-normal rainfall but "no clear evidence to suggest that [either] the strength and variability of the Indian Monsoon Rainfall (IMR) nor the epochal changes are affected by the global warming."

- Similar conclusions have been reached by several other authors. For example, "Singh (2001) investigated the long term trends in the frequency of cyclonic disturbances over the Bay of Bengal and the Arabian Sea using 100-year (1890–1999) data and found significant decreasing trends." Kripalani *et al.* find "no support for the intensification of the monsoon nor any support for the increased hydrological cycle as hypothesized by [the] greenhouse warming scenario in model simulations." They conclude "the analysis of observed data for the 131-year period (1871–2001) suggests no clear role of global warming in the variability of monsoon rainfall over India," much as Kripalani and Kulkarni (2001) had concluded two years earlier.
- Kanae *et al.* (2004) examined the number and intensity of heavy precipitation events by comparing a climate-model-derived hypothesis with digitalized hourly precipitation data recorded at the Tokyo Observatory of the Japan Meteorological Agency for 1890–1999. The authors report many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s, making the 1990s seem to be unprecedented, but they note "hourly heavy precipitation around the 1940s is even stronger/more frequent than in the 1990s." Their plots of maximum hourly precipitation and the number of extreme hourly precipitation events both rise fairly regularly from the 1890s to peak in the 1940s, after which declines set in that bottom out in the 1970s. The trend then reverses again, to rise to endpoints in the 1990s that are not yet as high as the peaks of the 1940s.
- Touchan *et al.* (2003) developed two reconstructions of spring (May–June) precipitation for southwestern Turkey from tree-ring width measurements for the periods 1776–1998 and 1339–1998. The reconstructions show clear evidence of multiyear to decadal variations in spring precipitation, but both dry and wet periods of 1–2 years were well distributed throughout the records. With respect to more extreme events, the period that preceded the Industrial Revolution stood out, for "all of the wettest 5-year periods occurred prior to 1756" while the longest period of reconstructed spring drought was the four-year period 1476–1479, and the single driest spring was 1746. Turkey's greatest precipitation extremes occurred well before the late twentieth century warm period.
- In a modeling study, Kim *et al.* (2012) assessed the seasonal predictive skill for the Asian monsoon for 1982–2009 by comparing retrodictions of the ECMWF System 4 (SYS4) and NCEP CFS version 2 (CFSv2) models with actual temperature and rainfall records. The models were found to perform poorly, exhibiting both regional warm (North Pacific and North Atlantic) and cold (Southern Hemisphere) temperature biases; excessive precipitation along the Intertropical Convergence Zone; and both stronger (SYS4 model) and weaker (CFSv2 model) projections of monsoon trade winds.

Conclusions

The evidence from the Middle East, Asia, and Japan provides no support for the claim that monsoon precipitation becomes more variable and intense in a warming world. In some cases the data suggest the opposite, and overall they provide support for the proposition that precipitation responds mostly to cyclical variations in solar activity.

The results of Kim *et al.* (2012) demonstrate there is a long way to go before GCM models can be viewed as reliable monsoon management aids. In addition, the results of Wang *et al.* (2013) suggest a better understanding of the role of internal feedback processes as captured by the ENSO, PDO, AMO, and other indices would provide a better approach to forecasting monsoon behavior than focusing solely on external forcings.

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6.1.3. Snowfall, Avalanches

On March 20, 2000, a British newspaper reported "Snowfalls are just a thing of the past" based on statements by a member of the Climatic Research Unit of the University of East Anglia, who claimed within a few years snowfall will become "a very rare and exciting event" and "children just aren't going to know what snow is." The U.K.'s Hadley Centre for Climate Prediction and Research said eventually British children would have only a "virtual" experience of snow via movies and the Internet.

A model developed at the U.S. National Oceanic and Atmospheric Administration (NOAA) published in the *Journal of Climate* projected the majority of the planet would experience less snowfall as a result of global warming due to increasing atmospheric CO_2. The predicted decline in snowfall was expected to cause serious problems for ski resorts and areas in the western United States that rely on snowmelt as a source of fresh water. Oregon and Washington would get less than half their usual amount of snow.

In June 2013, more than 100 ski resorts, concerned global warming would reduce snowfall and curtail skiing, joined the Business for Innovative Climate and Energy Policy Climate Declaration urging Americans to "use less electricity," "drive a more efficient car," and choose "clean energy" to combat climate change and save their ski resorts. The 2007 report of the IPCC warns of a difficult future for the industry: "…snow cover area is projected to contract[,] … mountainous areas will face glacier retreat, reduced snow cover and winter tourism[, and] … shifting of ski slopes to higher altitudes."

And yet, three of the top five snowiest winters in the Northern Hemisphere on record have occurred in the past five years (Figure 6.1.3.1).

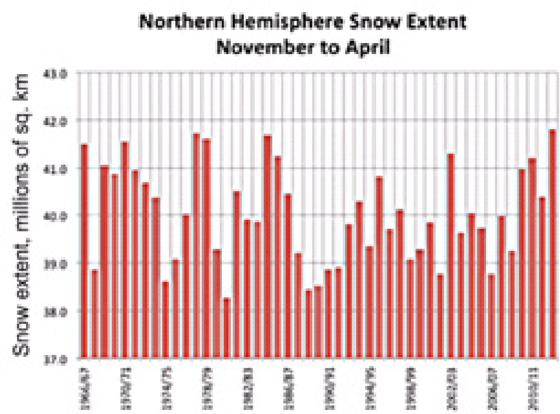

Figure 6.1.3.1. Annual winter snow extent in the Northern Hemisphere, November to April, 1966–2013 (Rutgers University, Global Snow Lab).

In related research, Eckert *et al.* (2010) examined the hypothesis that global warming might cause a dangerous increase in numbers of snow avalanches in the French Alps. Because avalanches are mainly governed by temperature fluctuations in combination with heavy snow and strong wind regimes, both Eckert *et al.* and the IPCC have deemed it likely they will be strongly influenced by climatic fluctuations. Eckert *et al.* analyzed snow avalanches using data from the *Enquete Permanente sur les Avalanches*—EPA, a chronicle that describes avalanche events on approximately 5,000 determined paths in the French Alps and the Pyrenees.

Eckert *et al.* found no strong changes in mean avalanche activity or in the number of winters of low or high activity over the last 60 years of record. Similar results have been reported from the Swiss Alps for the second half of the twentieth century by Laternser and Schneebeli (2002) and by other researchers, including Schneebeli *et al.* (1997) and Bader and Kunz (2000), who report no change in extreme snowfalls and catastrophic avalanches around

Davos, Switzerland during the twentieth century. Jomelli *et al.* (2007) found "no correlation between the fluctuations in avalanche activity between 1978 and 2003 and large-scale atmospheric patterns" in the Maurienne Valley in France, and Jomelli and Pech (2004) suggest avalanche magnitude at low altitudes has declined since 1650 in the Massif des Ecrins in the French Alps.

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Earlier Research

Other recent studies of the relationship between global warming and snow or avalanche activity include the following:

- Kunkel *et al.* (2009a and 2009b) used 440 long-term, homogeneous snowfall records to examine "temporal variability in the occurrence of the most extreme snowfall years, both those with abundant snowfall amounts and those lacking snowfall," defined as the highest and lowest tenth percentile winter snow amounts. Their data came from the conterminous United States over the 107-year period from 1900–1901 to 2006–2007.

Kunkel *et al.* (2009b) found large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States, balanced by large increases in the frequency of low-extreme snowfall years in the northeast, southeast, and northwest. The scientists determined overall "the area-weighted conterminous United States results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-year period."

- Kilpelainen *et al.* (2010) report on the degree to which Finnish forests are damaged by snow load on their branches, claiming across Europe such loading "has accounted for a mean annual amount of almost one million cubic meters of damaged wood in managed forests over the period 1950–2000." Damage results primarily from stem breakage or bending when the soil is frozen, although trees also can be uprooted if the soil is not frozen, and damage by insects or fungal attacks are common in trees suffering from snow damage.

To calculate risk of snow-induced damage, Kilpelainen *et al.* employed a snow accumulation model in which cumulative precipitation, air temperature, and wind speed were derived from the A2 scenario of the FINADAPT project (Ruosteenoja *et al*., 2005), where the air's CO_2 concentration was estimated to rise to 840 ppm by 2100 and mean air temperatures were projected to increase by almost 4°C in summer and more than 6°C in winter. The model was tested and trained using real-world data obtained by the Finnish Meteorological Institute (Venalainen *et al.*, 2005) for the 30-year baseline period of 1961–1990.

Defining the risk of snow-induced forest damage as proportional to the number of days per year when the accumulated amount of snow exceeds 20 kg m-2, the six scientists calculated the mean annual number of risk days in Finland declined by 11 percent, 23 percent, and 56 percent relative to the 1961–1990 baseline period for the first, second, and third 30-day simulation periods they modeled (1991–2020, 2021–2050, and 2070–2099), respectively. For the most hazardous areas of northwest and northeast Finland they also report "the number of risk days decreased from the baseline period of over 30 days to about 8 days per year at the end of the century."

- Peng *et al.* (2010) used snow-depth measurements collected at 279 meteorological stations in northern China, plus colocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate changes in snow depth for 1980–2006 and to analyze the effects of those changes on vegetative growth during the following spring and summer. Peng *et al.* report winter snow depth overall increased in northern China over the past 30 years, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed. Here, positive correlations exist between mean winter snow depth and spring NDVI data. In addition, they note Piao *et al.* (2005) had determined the net primary productivity of the same desert and grasslands during 1982–1999 "increased by 1.6% per year and 1.1% per year, respectively" and "desertification has been reversed in some areas of western China since the 1980s," as reported by Runnstrom (2000), Wu (2001), Zhang *et al.* (2003), and Piao *et al.* (2005). Peng *et al.* conclude the "increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms." They further note the frequency of sand-dust storms has "declined in China since the early 1980s (Qian *et al.*, 2002; Zhao *et al.*, 2004)."

- Teich *et al.* (2012) analyzed 21 snow and weather variables associated with 189 winter forest avalanches in the Swiss Alps between 1985 and 2006, an acknowledged human hazard (Bebi *et al.*, 2009; Martin *et al.*, 2001). The avalanches were spread geographically throughout the Alps and at heights ranging from 700 to 2,200 m height. The researchers found the number of potential forest avalanche days decreased at 11 of 14 snow and weather stations [79 percent] for new snow forest avalanches and at 12 of 14 stations [86 percent] for old snow forest avalanches, independent of elevation and climatic region. They conclude such "negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under current climate change." Thus, noting the currently observed increase in forest cover density in the Swiss Alps (Bebi *et al.*, 2001; Brandi, 2010; Krumm *et al.*, 2011), "it is likely that avalanche releases in forested terrain will become less frequent in the future."

Conclusions

The cited studies indicate a warming generally does not affect the frequency of avalanches. For instance, and after a comprehensive review of the work of other scientists, Eckert *et al.* (2010) conclude "climate change has recently had little impact on the avalanching rhythm in this region [the French Alps]." Regarding forest damage, the decline in the number of risk days reported from northern Finland by Kilpelainen *et al.* (2010) represents a warming-induced *decrease* in risk of snow damage to forests on the order of 75 percent.

Peng *et al.*'s (2010) studies show as the world has warmed over the past three decades, China above 40°N latitude has seen an increase in winter snow depth that has promoted increased vegetative growth in desert areas and grasslands and resulted in a reduction in sand-dust storms. These climate-related changes are obviously positive developments.

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6.1.4. Evaporation

Evaporation is the primary source of atmospheric water vapor, a powerful greenhouse gas, and so is of particular interest to climate scientists. Huntington (2006) notes direct measurements of evaporation (pan evaporation) show a reduction in evaporation over the twentieth century, whereas indirect estimates suggest an increase.

Roderick and Farquhar (2002) linked a reduction in pan evaporation rates to a reduction in insolation (solar dimming) at ground level due to increasing cloud cover and atmospheric aerosols. Subsequently Roderick *et al.* (2009a) calculated a reduction of 4.8 W/m^2 for Australia as driving the observed reduction in pan evaporation. The Australian results are extended to the global behavior by Roderick *et al.* (2009b), where a global reduction in pan evaporation is attributed to a combination of wind stilling and solar dimming. The authors also observe the interpretation of pan evaporation depends on whether the observations are from water-limited or energy-limited sites. For energy-limited sites, the evaporation occurs at the maximum rate possible for the radiative flux present, and declining pan evaporation also indicates declining evapo-transpiration. For water-limited sites, evaporation is restricted by the available water, and evapo-transpiration depends on the supply of precipitation. Therefore, Roderick *et al.* argue evapo-transpiration can rise while pan evaporation decreases, if the supply of precipitation increases sufficiently. This implies dry areas are getting wetter.

Recognizing the importance of near-surface wind speed for evaporation, McVicar *et al.* (2010) noted the "occurrence of widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years," citing papers by Roderick *et al.* (2007), McVicar *et al.* (2007; 2008), Pryor *et al.* (2009), and Jiang *et al.* (2010). Such a change, now widely termed "stilling," will be a key factor in reducing the atmospheric demand that drives actual evapotranspiration when water availability is not limited, as in the case of lakes and rivers.

In addition, McVicar *et al.* note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases (as demonstrated by McVicar *et al.*, 2007). Increasing wind speeds, they point out, lead to increases in atmospheric evaporative demand, and decreasing wind speeds do the opposite. These changes are significant for people who depend on water resources derived from mountainous headwater catchments: More than half the world's population lives in catchments with rivers originating in mountainous regions (Beniston, 2005), and this water supports about 25 percent of the global gross domestic product (Barnett *et al.*, 2005).

Defining u_z as change in wind speed with change in elevation—that is, $u_z = \Delta u/\Delta z$, where $\Delta u = u_2 - u_1$, $\Delta z = z_2 - z_1$, and $z_2 > z_1$—McVicar *et al.* calculated monthly averages of u_z, using 1960–2010 monthly average u data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China, and by MeteoSwiss at 37 sites in Switzerland. They suggest their research constitutes "the first time that long-term trends in u_z

in mountainous regions have been calculated," and their u_z trend results show u to have declined more rapidly at higher than at lower elevations in both study areas.

The double benefit of a decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations should act to reduce water loss via evaporation from high-altitude catchments in many of the world's mountainous regions, thus providing more water for people who obtain it from those sources. As McVicar *et al.* note, the "reductions in wind speed will serve to reduce rates of actual evapo-transpiration partially compensating for increases in actual evapo-transpiration due to increasing air temperatures."

Some papers in the literature (e.g., Cai *et al.*, 2009), and also the published IPCC fourth and draft fifth *Assessment Reports*, confuse the causal physics of the relationship between temperature and evapotranspiration by assuming increasing temperature causes drought. In reality, when incoming radiation falls on a moist surface this energy is partitioned into evapotranspiration (latent heat) and heating of the near surface/atmosphere (sensible heat). During drought, where moisture is limited, less of the incoming energy can be used for latent heat (i.e., reduced evapotranspiration) and consequently more sensible heat occurs. The consequence is that air temperatures rise as evapotranspiration is reduced (Lockart *et al.*, 2009a, b).

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6.1.5. Drought

Even a moderate drought can have devastating effects on regional agriculture, water resources, and the environment. Many climate scientists and agriculturists have expressed growing concern about worldwide drying of land areas and increasing evapo-transpiration, which they attribute to man-induced global warming. Some recent peer-reviewed studies suggest the severity and length of droughts is increasing over various regions due to global warming (e.g., Briffa *et al.*, 2009; Cai *et al.*, 2009). But in the United States, droughts have become shorter, less frequent, less severe, and less widespread over the past century, peaking during the Dust Bowl era of the 1930s, as clearly evidenced by the heat wave index for the period 1895–2008 (Figure 6.1.5.1).

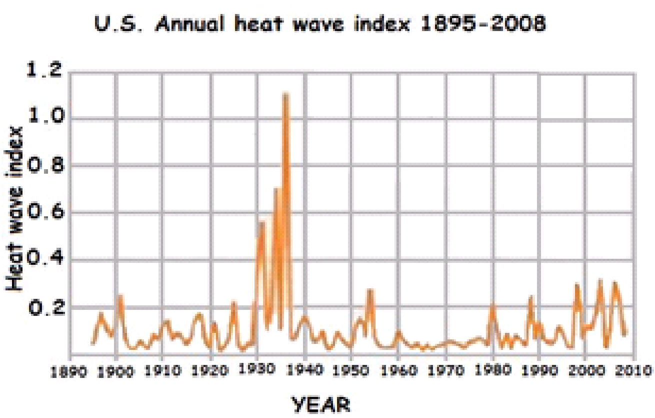

Figure 6.1.5.1. Heat Wave Index for USA, 1895–2008 (NOAA CCSP U.S. Climate Change Science Program, 2009).

Drought represents moisture deficit and therefore is an end-member of the precipitation spectrum. Many of the papers discussed earlier have referred to the issue. We include here several other important papers for which drought is the primary focus.

- Providing a long-term perspective of the climate cycle that stretches from the Medieval Warm Period to the late twentieth century warming, Laird *et al.* (2012) developed diatom-based proxy records for sediment cores from six lakes that provide a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada. The study was intended to address concerns that droughts similar to, or more extreme than, the 1930s Dust Bowl drought are a likely outcome of human-forced global warming and could perhaps last for several decades to centuries (Seager *et al*., 2007; Cook *et al*., 2010; Romm, 2011). A consequence of such droughts is decreased lake levels and river flows (Schindler and Lee, 2010).

Laird *et al*. reported a synchronous change had occurred across all of the six lakes, indicating "a period of prolonged aridity" during the Medieval Warm Period (c. 900–1400 AD). The general coincidence in time of this event at the six sites suggests an extrinsic climate forcing (Williams *et al.*, 2011) of natural origin. A parallel study by Schmieder *et al.* (2011) of five topographically closed lakes in Nebraska "indicated relative (climate) coherency over the last 4000 years, particularly during the MCA [Medieval Climate Anomaly] with all lakes indicating lake-level decline." Schmieder *et al*. also report "in Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al*., 2008), high eolian deposition occurred from ~1280 to 1410 AD in Elk Lake (Dean, 1997) and $\delta^{18}O$ from calcite indicated an arid period from ~1100 to 1400 AD in Steel Lake (Tian *et al*., 2006)." They note, "in Manitoba, the cellulose $\delta^{18}O$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 AD, and a less-severe dry period from 1320 to 1340 AD (Buhay *et al*., 2009)" and relatively warm conditions during the Medieval Warm Period "have been inferred from pollen records in the central boreal region of Canada and in Wisconsin" (Viau and Gajewski, 2009; Viau *et al*., 2012; Wahl *et al*., 2012)."

- In a study of drought in the global context over the past 60 years, Sheffield *et al.* (2012) utilize datasets on temperature, precipitation, and surface energy parameters (wind, specific humidity, etc.) to calculate the standard Palmer Drought Severity Index (PDSI) using two different equations. The PDSI-TH (Thornwaite formulation of evapotranspiration) and PDSI-PM (Penman-Montheith formulation) differ in that the TH model estimates evapotranspiration on the basis of air temperature (a proxy for potential evapotranspiration, not because of causal physics), whereas PM offers a more physically based evapotranspiration formulation, where temperature is utilized only to calculate near surface atmosphere humidity deficit. The TH model implicitly assumes no trend in air temperatures over the long term. The PDSI-TH approach overestimates evapotranspiration as long-term trends in temperature are apparent. The PDSI-PM equation does not respond to the temperature trend, as temperature is only an indirect variable.

Both the older, conventional index (PDSI-TH) and the newer index (PDSI-PM) show an increase in drought over recent years, though the trend for the latter was not statistically significant. The regions of decreasing trends in potential evaporation are in general agreement with areas of global dimming, decreasing wind speed, and changes in other surface parameters but not temperature. These results suggest previous calculations of global drought have been overestimated, and the authors conclude their study has implications for understanding changes in the terrestrial hydrological cycle and the future impacts of global warming on agriculture and water resources. Sheffield *et al.* (2009) arrived at similar conclusions.

Conclusions

The relationship between the occurrence of drought and global warming is, at best, weak. Nonetheless, in some places, such as North America, severe droughts occurred during the Medieval Warm Period. Given the absence of similar droughts during the warming in the late twentieth century, two conclusions follow. First, the Medieval Warm Period must have been more extreme in terms of both high temperature and its duration than anything experienced recently. Second, the occurrence of such extra warming is strong evidence that warmings greater than the recent one can occur without any help from rising atmospheric CO_2 concentrations, which were more than 100 ppm less during the Medieval Warm Period than they are today. This research thus suggests both recent warming and drought are the result of something other than anthropogenic CO_2 emissions.

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6.1.6. Rivers and Streamflow

Model projections suggest CO_2-induced global warming may induce large changes in global streamflow characteristics, which has led many authors and the IPCC to claim warming will lead to the intensification of the hydrological cycle and the occurrence of more floods (Labat, 2004; Huntington, 2006; Gerten *et al.*, 2008; Dai *et al.*, 2009).

Accordingly, many scientists have examined streamflow, or proxy streamflow, records in an effort to elucidate these claimed relationships. On the assumption that global runoff represents an integrated response to continental hydrological dynamics, some authors invert the reasoning and use changes in hydrology as an indicator of global warming (Gleick, 2003; Nilsson *et al.*, 2005; Milliman *et al.*, 2008). These matters relate to forecasts of precipitation variability, floods, and droughts, issues also addressed elsewhere in this chapter.

In a pivotal study of this relationship that formed part of the World Climate Program supported by UNESCO and the WMO, Kundewicz *et al.* (2004) analyzed long-term and high-quality data on streamflow to determine whether floods have increased worldwide, as predicted by climate models. They concluded, "the analysis of 195 long time series of annual maximum flows, stemming from the GRDC holdings does not support the hypothesis of general growth of flood flows. … Observations to date provide no conclusive and general proof as to how climate change affects flood behaviour. There is a discontinuity between some observations made so far. Increases in flood maxima are not evident whilst model-based projections show a clear increase in intense precipitation."

Milliman *et al.* (2008) examined discharge trends over the second half of the twentieth century for 137 rivers whose combined drainage basins represent about 55 percent of world land area. They found "between 1951 and 2000 cumulative discharge for the 137 rivers remained statistically unchanged," as did global on-land precipitation over the same period.

Munier *et al.* (2012) also estimated global runoff for the period 1993–2009, using two methods both of which were derived by coupling modeled land-atmosphere and ocean-atmosphere water budgets with independent datasets in order to estimate water storage variations in several water budget compartments. The datasets included atmospheric re-analyses, land surface models, satellite altimetry, and direct ocean temperature measurements. The results of both sets of calculations of global runoff correlate well for the full period 1993–2006. The researchers found "no significant trend … over the whole period" for either method of calculation. They conclude, "an intensification of the global water cycle due to global warming is not obvious over the last two decades."

Conclusions

The IPCC hypothesis regarding changes in streamflow should have been tested by these studies, but the hypothesis is so loosely formulated as to be essentially untestable. Predicting global warming will lead to more frequent and/or more intense flooding and drought, as the IPCC does, ensures predictive success for just about any dataset studied for any time and any place.

Nevertheless, none of the Kundzewicz *et al.* (2004), Milliman *et al.* (2008), or Munier *et al.* (2012) studies was able to identify any change in global runoff over the past 60 years. The simplest and most obvious conclusion to draw is that of Milliman *et al.* (2008), who report "neither discharge nor precipitation changed significantly over the last half of the 20th century, offering little support to a global intensification of the hydrological cycle."

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Earlier Research

Here we summarize other studies that address whether late twentieth century warming might have caused changes in streamflow regimes.

- Lins and Slack (1999) analyzed streamflow trends for 395 climate-sensitive stations, including data from more than 1,500 individual gauges, located throughout the United States, the longest datasets stretching back to 1914. They found many more flow up-trends than down-trends, with slight decreases occurring "only in parts of the Pacific Northwest and the Southeast." Their findings indicate "the conterminous U.S. is getting wetter, but less extreme."
- Brown *et al*. (1999) studied siliciclastic sediment grain size, planktonic foraminiferal and pteropod relative frequencies, and the carbon and oxygen isotopic compositions of two species of planktonic foraminifera in cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico to delineate the changing characteristics of the Mississippi River over the past 5,300 years. They identified the occurrence of large megafloods—which they describe as having been "almost certainly larger than historical floods in the Mississippi watershed"—at 4,700, 3,500, 3,000, 2,500, 2,000, 1,200, and 300 years before present. These flow events probably related to times of export of extremely moist Gulf air to midcontinental North America, driven by naturally occurring millennial and multidecadal oscillations in Gulf of Mexico ocean currents.
- Hidalgo *et al.* (2000) used principal components analysis to reconstruct streamflow in the Upper Colorado River Basin from tree-ring data, comparing their results with the streamflow reconstruction of Stockton and Jacoby (1976). Their work supported the earlier study but delivered a better understanding of periods of below-average stream-flow or regional drought. Hidalgo *et al.* identify "a near-centennial return period of extreme drought events in this region" that stretched back to the early 1500s, and their data suggest the existence of past droughts that surpassed the worst of the twentieth century.
- Pederson *et al*. (2001) used tree-ring chronologies from northeastern Mongolia to develop annual precipitation and streamflow histories for the period 1651–1995. The research revealed variations over the recent period of instrumental data are not unusual relative to the prior record, as judged against the standard deviation and five-year intervals representative of extreme wet and dry periods. Although the reconstructions "appear to show more frequent extended wet periods in more recent decades," Pederson *et al.* conclude this observation does not provide "unequivocal evidence of an increase in precipitation as suggested by some climate models." Spectral analysis of the data also revealed significant periodicities of 12 and 20–24 years, hinting at the presence of a solar influence.
- Knox (2001) studied how conversion of the U.S. Upper Mississippi River Valley from prairie and forest to crop and pasture land in the early 1800s influenced subsequent watershed runoff and soil erosion rates. Initially, the conversion of the region's natural landscape to agricultural use increased surface erosion rates by three to eight times those characteristic of pre-settlement times. The land-use conversion also increased the peak discharges from high-frequency floods by 200 to 400 percent. Since the late 1930s, however, surface runoff has been decreasing. The decrease "is not associated with climatic causes," according to Knox, who reports an analysis of the variation in storm magnitude over the same period showed no statistically significant trend.
- Molnar and Ramirez (2001) conducted an analysis of precipitation and streamflow trends for the period 1948–1997 in a semiarid region of the southwestern United States, the Rio Puerco Basin of New Mexico. They reported "a statistically significant [annually] increasing trend in precipitation in the basin was detected." This trend was driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range, with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale; monthly totals increased in low-flow months and decreased in high-flow months.
- Hisdal *et al*. (2001) analyzed more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and

frequency of drought over the following four time periods: 1962–1990, 1962–1995, 1930–1995, and 1911–1995. They concluded, "despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied." On the contrary, the trends pointing toward decreasing streamflow deficits or fewer droughts outnumbered trends of increasing streamflow deficits or more droughts.

- Cluis and Laberge (2001) checked for recent changes in runoff at 78 rivers "geographically distributed throughout the whole Asia-Pacific region," using streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany). Mean start and end dates of the river flow records were 1936 ± 5 years and 1988 ± 1 year. The researchers determined mean river discharges were unchanged in 67 percent of the cases investigated; where trends did exist, 69 percent were for lesser flows. Maximum river discharges were unchanged in 77 percent of the cases investigated, and where trends did exist 72 percent were again downward. Minimum river discharges were unchanged in 53 percent of cases investigated; where trends existed, 62 percent of them were upward.
- Campbell (2002) analyzed grain size in 4,000-year-long sediment cores from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of climate variability. The research identified periods of both increasing and decreasing grain size (a proxy for moisture availability) throughout the 4,000-year record at decadal, centennial, and millennial time scales. The predominant departures from the background norm included several-centuries-long epochs that corresponded to the Little Ice Age (about AD 1500–1900), the Medieval Warm Period (about AD 700–1300), the Dark Ages Cold Period (about BC 100 to AD 700), and the Roman Warm Period (about BC 900–100). A standardized median grain-size history revealed the highest rates of stream discharge during the past 4,000 years occurred during the Little Ice Age, approximately 300–350 years ago, when grain sizes were about 2.5 standard deviations above the 4,000-year mean. By contrast, the lowest rates of streamflow were observed around AD 1100, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean. Grain size over the past 150 years generally has remained above average, with no indication of a climatic trend related to twentieth century warming.
- McCabe and Wolock (2002) evaluated U.S. records for 1895–1999 for three hydrologic parameters: precipitation minus annual potential evapotranspiration, the surplus water that eventually becomes streamflow, and the water deficit that must be supplied by irrigation to grow vegetation at an optimum rate. This investigation revealed a statistically significant increase in the first two of these parameters, and for the third there was no change, indicating water has become more available within the conterminous United States and there has been no increase in the amount of water required for optimum plant growth.
- Pekarova *et al*. (2003) analyzed annual discharge rates of selected large rivers of the world for recurring cycles of wet and dry. For rivers with long enough records, they also derived long-term discharge rate trends. The authors could not identify "any significant trend change in long-term discharge series (1810–1990) in representative European rivers," including the Goeta, Rhine, Neman, Loire, Wesaer, Danube, Elbe, Oder, Vistule, Rhone, and Po.
- McCabe and Clark (2005) used daily streamflow data representing snowmelt for 84 stations in the western United States, each with complete water-year information for the period 1950–2003. Each station's mean streamflow trend was determined for the past half century as well as any marked steps that may have occurred in each data series. As other researchers had reported previously, McCabe and Clark determined the timing of snowmelt runoff for many rivers in the western United States has shifted earlier, not as a trend but as a step change during the mid-1980s. This change occurred coincidentally with "a regional step increase in April-July temperatures during the mid-1980s." After discussing the possible reasons for these changes, McCabe and Clark conclude "the observed change in the timing of snow-melt runoff in the western United States is a regional response to natural climatic variability and may not be related to global trends in temperature."
- Carson and Munroe (2005) used tree-ring data collected by Stockton and Jacoby (1976) from the Uinta Mountains of Utah to reconstruct the mean annual discharge in the Ashley Creek watershed for the period 1637 to 1970. Significant persistent departures from the long-term mean occurred throughout the 334-year record of streamflow. The periods 1637–1691 and 1741–1897 experienced reduced numbers of extremely large flows and increased numbers of extremely small flows, indicative of persistent drought or near-drought

conditions. By contrast, there was an overall abundance of extremely large flows and relatively few extremely small flows during the periods 1692–1740 and 1898–1945, indicative of wetter conditions.

- Rood *et al*. (2005) analyzed streamflow trends for rivers fed by relatively pristine watersheds in the central Rocky Mountain Region extending from Wyoming (United States) through British Columbia (Canada). Both parametric and nonparametric statistical analyses were used to assess nearly a century of annual discharge (ending about 2002) along 31 river reaches that drain this part of North America. They found river flows in the region declined over the past century by an average of 0.22% per year, with four of them exhibiting recent decline rates exceeding 0.5% per year. This finding "contrasts with the many current climate change predictions that [this] region will become warmer and wetter in the near-future."
- Déry and Wood (2005) analyzed hydrometric data for 1964–2003 from 64 northern Canadian rivers that drain more than half of the country's landmass. After assessing variability and trends in the data, they explored the influence of large-scale teleconnections on the data record. They identified a statistically significant mean decline of approximately 10 percent in the discharge rates of the 64 rivers over the four decades of their study, matching a decline in precipitation known for northern Canada between 1964 and 2000. Déry and Wood conclude the decline in river discharge was driven "primarily by precipitation rather than evapotranspiration." They also report statistically significant links between the declines in precipitation and streamflow and the Arctic Oscillation, the El Niño/Southern Oscillation, and the Pacific Decadal Oscillation. No influence was discerned from twentieth century warming per se.
- Cao *et al.* (2006) conducted a streamflow study for the Qinghai-Tibet Plateau to evaluate theoretical arguments and models that suggest deleterious human-caused changes in streamflow might occur there (Houghton *et al.*, 2001; Rahmstorf and Ganopolski, 1999; Bruce *et al.*, 2002). The modeled scenarios suggest global warming should cause a precipitation increase in northwest China, with one researcher predicting a regional climatic shift from warm-dry to warm-wet (Shi, 2003) accompanied by an increase in total river discharge.

Cao *et al*. analyzed annual discharge data for five large rivers of the Qinghai-Tibet Plateau over the period 1956–2000, using the Mann-Kendall nonparametric trend test. They determined "river discharges in the Qinghai-Tibet Plateau, in general, have no obvious change with the increase of the Northern Hemisphere surface air temperature," and therefore with late twentieth century warming.

- Woodhouse *et al*. (2006) generated updated proxy reconstructions of streamflow for four key gauges in the Upper Colorado River Basin (Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona). They determined the major drought of 2000–2004, "as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record," and "average reconstructed annual flow for the period 1844–1848 was lower." They also report "two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004," and six other periods "have a 10% or greater chance of being drier." They conclude their "analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate" and "droughts more severe than any 20th to 21st century event [have] occurred in the past."
- Novotny and Stefan (2006) analyzed Nevada (USA) streamflow records prior to 2002 from 36 gauging stations in five major river basins, with lengths ranging from 53 to 101 years. They derived seven annual streamflow statistics: mean annual flow, seven-day low flow in winter, seven-day low flow in summer, peak flow due to snowmelt runoff, peak flow due to rainfall, and high and extreme flow days. Significant trends occurred for each of the seven statistics somewhere in the state, but in most cases the trends are not monotonic but periodic. Not surprisingly, "the mean annual stream flow changes are well correlated with total annual precipitation changes."

With respect to extreme hydrological events, Novotny and Stefan found peak flood flows due to snowmelt runoff "are not changing at a significant rate throughout the state," but seven-day low flows or base flows are "increasing in the Red River of the North, Minnesota River and Mississippi River basins during both the summer and winter" and the "low flows are changing at a significant rate in a significant number of stations and at the highest rates in the past 20 years." They note "this finding matches results of other studies which found low flows increasing in the upper Midwest region including Minnesota (Lins and Slack, 1999; Douglas *et al*., 2000)."

The changes Novotny and Stefan described are mostly beneficial, because "water quality and aquatic ecosystems should benefit from increases in low flows in both the summer and winter, since water quality stresses are usually largest during low flow periods." In addition, they note, "other good news is that spring floods (from snowmelt), the largest floods in Minnesota, have not been increasing significantly."

- Woodhouse and Lukas (2006) developed a network of 14 annual streamflow reconstructions, 300 to 600 years long, for the Upper Colorado and South Platte River basins, Colorado, based on tree-ring chronologies. The authors conclude "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries"; and further, "paleoclimatic studies indicate that the natural variability in 20th century [streamflow] gage records is likely only a subset of the full range of natural variability," as discovered also by Stockton and Jacoby (1976), Smith and Stockton (1981), Meko *et al*. (2001), and Woodhouse (2001). They conclude "multi-year drought events more severe than the 1950s drought have occurred" and "the greatest frequency of extreme low flow events occurred in the 19th century," with a "clustering of extreme event years in the 1840s and 1850s."
- Davi *et al*. (2006) used tree-ring-width chronologies from five sampling sites in west-central Mongolia to develop precipitation models. The longest of the five tree-ring records (1340–2002) was used to reconstruct a proxy streamflow record for 1637–1997. Davi *et al.* report there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation [1937–2003]." Their streamflow history indicates "the wettest 5-year period was 1764–68 and the driest period was 1854–58," while "the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83."
- MacDonald *et al*. (2007) used tree-ring records from northern Eurasia to provide reconstructions back to AD 1800 of annual discharge for the major rivers that enter the Arctic Ocean: S. Dvina, Pechora, Ob', Yenisey, Lena, and Kolyma. Annual discharges in the mid to late twentieth century were not significantly greater than discharges experienced over the preceding 200 years and "are thus still within the range of long-term natural variability." MacDonald *et al.* also found "longer-term discharge records do not indicate a consistent positive significant correlation between discharge [and] Siberian temperature," but instead a weak *negative* correlation over the period of their study.
- St. George (2007) used streamflow data from the Winnipeg River watershed to assess Burn's (1994) suggestion that a doubling of the air's CO_2 content might increase the severity and frequency of droughts in the prairie provinces of Canada (Alberta, Saskatchewan, Manitoba), an assertion that conflicts with climate modeling suggesting runoff in Manitoba instead could increase 20 to 30 percent by 2050 (Milly *et al.*, 2005). St. George assembled streamflow data from nine gauge stations for the period 1924–2003 from the Water Survey of Canada's HYDAT data archive, with precipitation and temperature data taken from Environment Canada's Adjusted Historical Canadian Climate Data archive.

St. George's analysis showed "mean annual flows have increased by 58% since 1924 ... with winter streamflow going up by 60–110%," primarily because of "increases in precipitation during summer and autumn." A link to climate is suggested by the fact that similar "changes in annual and winter streamflow are observed in records from both regulated and unregulated portions of the watershed." However, other studies have reported declining flow for many rivers in the Canadian prairies (Westmacott and Burn, 1997; Yulianti and Burn, 1998; Déry and Wood, 2005; Rood *et al*., 2005). In essence, conflicting conclusions have been reached about the hydrology of the prairie provinces of Canada, especially in Manitoba, making it impossible to issue confident forecasts about future streamflows. Nonetheless, St. George asserts "the potential threats to water supply faced by the Canadian Prairie Provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin."

- Smith *et al*. (2007) presented an analysis of daily discharge records from 138 small to medium-sized unregulated rivers in northern Eurasia, with a focus on assessing low-flow trends since the 1930s. They conclude "a clear result of this analysis is that, on balance, the monthly minimum values of daily discharge, or 'low flows,' have risen in northern Eurasia during the 20th century" with the greatest minimum flow increases since ~1985.
- Mauas *et al.* (2008) studied Parana River, South America, streamflow data since 1904, when the daily record began. The river is the world's fifth-largest in terms of drainage area and fourth-largest with respect to streamflow. The researchers found "the flow of the Parana is larger in the last three decades, with a mean value almost 20% larger than that of the first 70 years of the twentieth century." They note "the stream flow during the last 30 years has increased in the months in which the flow is minimum, while the flow remains more or less constant during the months of maximum

... [and] … the same trend is also found in other rivers of the region."

Mauas *et al.* also report a strong correlation between solar parameters and periodicities present in the detrended time series of streamflow data. Both sunspot number and total solar irradiance correlate at a significance level greater than 99.99% with Pearson's correlation coefficients between streamflow and the two solar parameters of 0.78 and 0.69 respectively.

- Hannaford and Marsh (2008) utilized a U.K. benchmark network of 87 near-natural catchments (as identified by Bradford and Marsh, 2003) to appraise trends in high-flow regimes in catchments unaffected by human disturbances. They write, "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments, and projections suggest that flooding may increase in [the] future as a result of human-induced warming."

The two researchers report "significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK," with similar changes being absent from lowland areas in the south and east of the U.K. The high-flow indicators they observed in the northwest are correlated with the North Atlantic Oscillation (NAO), suggesting the recent upward trend in high-flow events may reflect one part of a multidecadal cycle.

- Lloyd (2010) studied flow trends in the Breede River, the largest in South Africa's Western Province and economically significant. Prior modeling studies had predicted flows into the river could be reduced dramatically by a warming climate (e.g., Steynor *et al.*, 2009). Steynor *et al.* analyzed flow data for five sites in the Breede Valley to compute historical flow-rate trends over historic periods of warming ranging from 29 to 43 years in length. All the calculated future flow rates exhibited significant negative change, averaging -25% for one global climate model and -50% for another. The mean past trend of four of the five Breede River stations also was negative (-13%), with the remaining station indicating an increase of +14.6%. Lloyd noted "changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows" of the negative-trend stations.

Because Steynor *et al.* had presumed warming would lead to decreased flow, they assumed their projections were correct. Lloyd was able to demonstrate those results were driven primarily by unaccounted-for land use changes in the five catchments; the one site that had "a pristine watershed" was the one with the "14% increase in flow over the study period." Lloyd concluded his results were contrary to the climate change predictions and indicate "climate change models cannot yet account for local climate change effects."

- Panin and Nefedov (2010) provided a riverine geomorphological and archaeological study of the Upper Volga and Zapadnaya Dvina Rivers (Russia) to assess the hypothesis that human settlement on floodplains is controlled by the frequency of seasonal floods. Their database comprised occupational layers for 1,224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province.

Panin and Nefedov identified a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals associated with periods of warming and cooling, respectively. The period AD 1000–1300 Middle Ages provided particularly favorable conditions for floodplain settlement in areas subject to inundation today. Panin and Nefedov conclude this interval "can be regarded as hydrological analogues of the situation of the late 20th–early current century." This relationship implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

- Zhang *et al.* (2010) analyzed twentieth century daily streamflow for eight unregulated streams in the Susquehanna River Basin, USA. This basin includes parts of the states of Maryland, New York, and Pennsylvania and is the largest freshwater contributor to Chesapeake Bay, comprising 43 percent of the bay's drainage area and providing 50 percent of its water. The records studied start at slightly different times, but all end in 2006 with record-lengths ranging from 68 to 93 years and an average length of 82.5 years. The data were subjected to monotonic trend tests, each of which used different beginning and ending times, to detect changes and trends in annual minimum, median, and maximum daily streamflow.

Zhang *et al.* found annual maximum streamflow "does not show significant long-term change," but there was "a considerable increase in annual minimum flow for most of the examined watersheds, and a noticeable increase in annual median flow for about half of the examined watersheds."

- Hannaford and Buys (2012) analyzed trends in U.K. river flow between 1969 and 2008 in a network of 89 near-natural catchments in an attempt to distinguish natural climate-driven trends from direct anthropogenic disturbances. Previous model studies have suggested the U.K. will experience wetter winters and hotter, drier summers in the future, causing decreasing river flow in summer and increases in winter (Murphy *et al.* 2009; Arnell, 2011; Prudhomme *et al*., 2012), with increases in flood frequency and magnitude in some regions (Arnell, 2011; Kay and Jones, 2012; Bell *et al*., 2012). Real-world data, however, indicate droughts in 2004–2006 (Marsh *et al*., 2007) and 2010–2012 (Marsh, 2012) were caused by successive dry winters, while a sequence of wet summers occurred in the 2007–2012 period (e.g., Marsh and Hannaford, 2008).

In apparent harmony with climate model projections, Hannaford and Buys observed "an overall increase in winter river flows." But in conflict with what the models predict, they report "in summer, there is no compelling evidence for a decrease in overall runoff or low flows, which is contrary to trajectories of most future projections." More specifically, they found the predominance of increasing flow trends across the seasons, coupled with limited decreases in low flows, is favorable from a water management perspective; the lack of any tendency toward decreasing river flow (for summer and for low flows especially) contradicts model expectations under assumed global warming scenarios; and the lack of decreasing river flow indicates a robustness and resilience of hydrology to warming trends.

- Khoi and Suetsugi (2012) evaluated seven climate models—CMIP3 GCMs-CCCMA CGCM3.1, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM3.0, UKMO HadGEM1, and UKMO Had CM3—to determine which was most successful in predicting rates of streamflow in Vietnam's Be River Catchment. The IPCC's SRES emission scenarios A1B, A2, B1, and B2 were adopted, along with prescribed increases in global mean temperature ranging between 0.5 and 6°C.

GCMs consistently have projected increases in the frequency and magnitude of extreme climate events, and variability of precipitation, leading some authors to conclude "this will affect terrestrial water resources in the future, perhaps severely" (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Chen *et al*., 2011). Khoi and Suetsugi's findings, however, indicate "the greatest source of uncertainty in impact of climate change on streamflow is GCM structure [choice of GCM]," noting the range of uncertainty could have increased even further if a larger number of GCMs had been deployed. Similar findings have been made by other authors, including Kingston and Taylor (2010), Kingston *et al*. (2011), Nobrega *et al*. (2011), Thorne (2011), and Xu *et al*. (2011). Khoi and Suetsugi conclude "single GCM or GCMs ensemble mean evaluations of climate change impact are unlikely to provide a representative depiction of possible future changes in streamflow."

Conclusions

There appears to be little support in real-world data for the contention that CO_2-induced global warming will lead to more frequent and/or more severe increases and decreases in streamflow that result in, or are indicative of, more frequent and/or more severe floods and droughts. Observed trends appear to be just the opposite of what is predicted to occur, and nearly all observed real-world changes are either not deleterious or are beneficial, and often extremely so. For example:

- Lins and Slack (1999) report the United States has become wetter in the mean and less variable in the extremes during warming over the last century.

- Brown *et al.* (1999) have shown the 1999 Mississippi floods were not related to changes in atmospheric CO_2.

- Campbell (2002) demonstrates there is nothing unusual about the moisture status of the Alberta region during the past 50 years compared to the record of the last millennium, and Déry and Wood (2005) similarly record no change in river flows in northern Canada over the past 60 years.

- Pekarova *et al.* (2003) show no long-term changes took place in the discharge of European rivers during the past 180 years, which period encompasses the passage between the end of the Little Ice Age and twentieth century climate.

- Cao *et al.* (2006) could detect no increase in stream discharge on the Tibetan Plateau during recent warming, and Davi *et al.* (2006) could find no evidence for any twentieth century long-term change in precipitation or streamflow.

Clearly, real-world data do not support the negative hydrologic effects the IPCC associates with both real-world and simulated global warming. At the same time, the paper by Khoi and Suetsugi (2012) demonstrates neither single GCMs nor GCM ensembles can currently provide representative estimates of future patterns of streamflow. Moreover, some studies identify solar factors (Brown *et al.*, 1999; Pederson *et al.*, 2001) or multidecadal cyclicity (Hannaford and Marsh, 2008; Mauas *et al.,* 2008) as more important influences on streamflow variability than is atmospheric CO_2.

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6.2. Oceans

Key Findings

The main findings of Section 6.2, Oceans, are:

- SEA-LEVEL CHANGE. Sea-level rise is one of the most feared impacts of any future global warming, but public discussion of the problem is beset by poor data, misleading analysis, an overreliance on computer model projections, and a failure to distinguish between global and local sea-level change—all of which has led to unnecessary and unjustified alarm.

- GEOLOGICAL CONTEXT OF SEA-LEVEL CHANGE. The maximum sustained rate of global sea-level rise during the most recent postglacial melting was about 10 mm/year, or 1 m/century. The main contributions to this rapid rate of rise, which occurred between about 20,000 and 10,000 years ago, came from melting of continental ice caps over North America and northwest Europe. Such ice caps no longer exist, and therefore a value of 10 mm/y is a realistic natural limit for the likely maximum rate of future sea-level rise should further ice melting ensue. More probably, rates will lie close to the observed twentieth century rate of sea-level rise of ~1.8 mm/y from all causes.

- DISTINGUISHING LOCAL FROM GLOBAL (EUSTATIC) SEA LEVEL. Virtually all public discussion that considers sea-level hazard is concerned with changes in the global average sea level. This notional statistic has little relevance to the practicalities of coastal planning and shoreline defense that are the concern of coastal engineers. Real-world coastal management is based upon knowledge of the rate of change of the local relative sea level at the site concerned. Local sea level is influenced as much by substrate subsidence or uplift, sediment supply, and meteorological and oceanographic factors as it is by the notional global average sea level. As it has been in the past, coastal hazard policy should be based upon local relative sea-level change as measured by appropriate and site-specific tide gauges, rather than upon speculative, model-driven prognostications of global average change.

- TIDE GAUGE MEASUREMENTS. Many studies of tide gauge datasets conclude the twentieth century saw a progressive rise in global sea level of between about 1.4 and 1.8 mm/y, modulated at a decadal or multidecadal scale by periods of lesser and greater rates of rise. Such conclusions, however, are based upon corrected tide gauge data, and some analyses of uncorrected data indicate a rate of rise of less than 1 mm/y.

- SATELLITE MEASUREMENTS. Satellite-mounted measurements of sea level made by radar ranging altimetry have been available since the early 1990s. Until recently, these measurements indicated a rate of global sea-level rise of more than 3 mm/y; i.e., about twice the rate measured by tide gauges. Over the past few years, however, the satellite-measured rate of rise has been closer to 2 mm/y, a figure that may overlap with the tide gauge measurements once errors are taken into account. Nonetheless, and to the degree they continue to indicate higher rates of sea-level rise than do tide gauge datasets, radar altimetric estimates of sea-level change should be treated circumspectly, for the complexity of their processing is so high the accuracy of the method has yet to be fully established.

- NATURAL SEA-LEVEL VARIABILITY. Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and control the oceans' response to atmospheric pressure. These processes vary on decadal and multidecadal time scales, especially with regard to a 60-year-long oceanographic cycle, which vitiates the usefulness of fitting linear trends to sea-level data over periods of less than about 120 years. The pitfall is especially great when shorter periods of time are used to infer an acceleration or deceleration of sea-level rise has occurred, because the existence of such rate changes is an intrinsic part of known natural multidecadal variability. Natural variability must be taken into account during any projection of future sea levels, yet scientists only recently have begun to incorporate it into their modeling.

- ACCELERATION OF SEA-LEVEL RISE. The IPCC's 2007 report projected global sea level was likely to rise by somewhere between 18 and 59 cm by 2100, and at an accelerating rate. Since then, several semi-empirical model analyses have predicted sea-level rises for the twenty-first century might even exceed one meter. However, multiple analyses of tide gauge and satellite records make it clear rates of global rise around 10 mm/y do not, and are not likely to, occur. Nearly all sea-level records show either a steady state of rise or a deceleration during the twentieth century, both at individual locations and for the global average. Though it is only an inadequate 20 years long, the satellite radar altimeter record also displays a recent deceleration of sea-level rise.

- DROWNING ATOLLS. On October 17, 2009, members of the Maldives' Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to oceanic atolls and islands. In contrast, observational and field evidence from a wide geographic range of low-lying ocean islands show low rates of sea-level rise consonant with the tide gauge global average. An oceanic atoll represents a dynamic sedimentary system sustained by broken coral detritus. Atoll integrity is jeopardized when subjected to human environmental pressures such as sand mining, construction project loading, and rapid groundwater withdrawal, all of which cause local lowering of the ground surface. It is these processes in combination with episodic natural hazards such as king tides and storms, not sea-level rise, that provide the alarming footage of marine flooding on Pacific Islands that from time to time appears on television news.

- ISOSTASY. The gravitational load induced on Earth's crust by growth of an ice sheet causes depression of the substrate and local sea-level rise; equally, ice cap melting removes the load and induces uplift and local sea-level fall. This effect is termed isostasy and must be corrected for in global sea-level estimates, generally by using an appropriate Glacial Isostatic Adjustment (GIA). GIA models lack independent verification but are informed by the best-available knowledge of Earth's actual shape, as measured from space in the form of a Terrestrial Reference Frame (TRF). Recently, NASA has indicated current TRF errors are greater than the inferred signal of sea-level change being measured, and the agency has proposed a new satellite be launched with the specific role of measuring the TRF accurately. Clearly, estimates of sea-level change made using satellite-borne altimetric data will remain problematic until the launch of NASA's new GRASP satellite, or until the development of some other mechanism for improving the accuracy of geoid models. As Wunsch *et al*. (2007) noted, "At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology."

- MODELS. Semi-empirical and GCM models of future sea-level change project a logarithmically increasing rate of rise. Their proponents argue that although current sea-level change is slow, this is because the response to temperature has a significant time lag and rates will become progressively faster (10 mm/y or more) in the future. In addition, it is assumed, without justification, that a projected global sea-level curve is also representative of local and regional sea-level changes. The controversy surrounding the likely accuracy and policy usefulness of published semi-empirical and GCM models of sea-level change remains unresolved. Given that simple empirical projections yield more modest projections of future sea level, semi-empirical and GCM model projections indicating higher and increasing rates of rise must be treated as speculative until their known flaws have been addressed.

- MELTING ICE. Accurate measures of the global area of sea ice and the volume of onland ice are available only for the satellite era, commencing in 1979. The complexity of correcting and interpreting data measured from near-Earth space is high, and hence significant uncertainty still attends our knowledge of the water balance of the world's oceans with respect to the melting of onland ice. Nonetheless, no strong evidence exists that either the Greenland or Antarctic ice sheet is wasting at greater than natural rates. Little recent change in global sea level can be attributed to enhanced melting of the modern ice sheets. For Antarctica such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall; in such circumstances the sum of the response of the whole Antarctic Ice Sheet might compensate for any long-term wastage of the Greenland Ice Sheet that might occur. As both Antarctica and Greenland have been cooling for the past half-century, it remains entirely possible the global cryosphere is actually growing in mass.

- OCEAN HEAT. At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 16 years of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming. Increasingly, this problem has been finessed by noting the atmosphere holds only a small percentage of the world's heat, and that what counts is the 93 percent of global heat sequestered in the oceans. Accurate measurements of ocean heat are available only since the 2003 deployment of the Argo system of diving buoys. The available Argo record shows no significant or accelerated ocean warming over the past nine years.

- OCEAN CIRCULATION. It has been asserted global warming will change the speed of major ocean currents such as the Gulf Stream in ways that will make the world's climate less hospitable. Worries also exist that onland ice melting could deliver enhanced volumes of freshwater to the Arctic Ocean and thereby shut down the critical source of sinking saline water that feeds deep water into the world ocean's thermohaline circulation. All components of ocean circulation vary naturally in flow volume or speed, and often in sympathy with climatic factors. No evidence exists for changes in the global ocean circulation system that lie outside the bounds of natural variation. Though this natural variation has yet to be fully described, evidence is lacking for any additional changes in circulation forced by human CO_2 emissions.

Introduction

To assess whether enhanced freshwater delivery to the Arctic Ocean by increased river flow could shut down the ocean's thermohaline circulation, Peterson *et al.* (2002) plotted annual values of the combined discharge of the six largest Eurasian Arctic rivers—Yenisey, Lena, Ob', Pechora, Kolyma, and Severnaya Dvina, which drain about two-thirds of the Eurasian Arctic landmass—against the globe's mean annual surface air temperature (SAT). They determined a simple linear regression trend through the data and concluded the combined discharge of the six rivers rises by about 212 km3/year in response to a 1°C increase in mean global air temperature. For the high-end global warming predicted by the Intergovernmental Panel on Climate Change (IPCC) to occur by AD 2100—i.e., a temperature increase of 5.8°C—they projected the warming-induced increase in freshwater discharge from the six rivers could rise by as much as 1,260 km3/year (we calculate 5.8°C x 212 km^3/year/°C = 1230 km3/year), a 70 percent increase over the mean discharge rate of the past several years.

It has been hypothesized that the delivery of such a large addition of freshwater to the North Atlantic Ocean may slow or even stop that location's production of new deep water, which constitutes one of the driving forces of the thermohaline circulation, the great oceanic "conveyor belt."

Although still discussed, this scenario is not as highly regarded today as it was when Peterson *et al.* conducted their research, for several reasons. For one, it is difficult to accept the tremendous extrapolation Peterson *et al.* make in extending their Arctic freshwater discharge vs. SAT relationship to the great length implied by the IPCC's predicted high-end warming of 5.8°C over the remainder of the current century. According to Peterson *et al.*, "over the period of the discharge record, global SAT increased by 0.4°C." It is implausible to extend the relationship they derived for that small temperature increase fully 14-and-a-half times further, to 5.8°C.

Consider also the Eurasian river discharge anomaly vs. global SAT plot of Peterson *et al.* (their Figure 4), which we have re-plotted in Figure 6.2.1. Enclosing their data with simple straight-line upper and lower bounds, it can be seen the upper bound of the data does not change over the entire range of global SAT variability, suggesting the upper bound corresponds to a maximum Eurasian river discharge rate that cannot be exceeded in the real world under its current geographic and climatic configuration. The lower bound, by contrast, rises so rapidly with increasing global SAT that the two bounds intersect less than two-tenths of a degree above the warmest of Peterson *et al.*'s 63 data points, suggesting 0.2°C beyond the temperature of their warmest data point may be as far as any relationship derived from their data may be validly extrapolated.

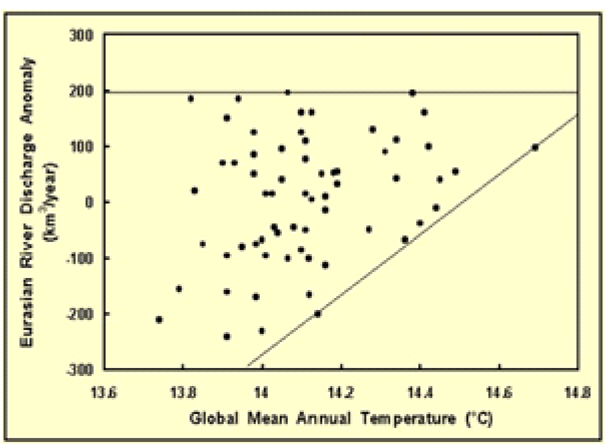

Figure 6.2.1. Annual Eurasian Arctic river discharge anomaly vs. annual global surface air temperature (SAT) over the period 1936 to 1999. Adapted from Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.

Reference

Peterson, B.J., Holmes, R.M., McClelland, J.W., Vorosmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., and Rahmstorf, S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298, 2171–2173.

6.2.1. Sea-level Change

Sea-level rise is one of the most feared impacts of any future global warming (Nicholls, 2011). But public discussion of the problem is beset by poor data, misleading analysis, and an overreliance on computer model projections, leading to unnecessary alarm.

A proper understanding of the risks associated with sea-level change can be attained only by maintaining a clear distinction between changes in global sea level (often also called eustatic sea level) and changes in local relative sea level. Sea-level changes are measured relative to a defined reference level, or datum. This datum is difficult to define over regional and global scales because Earth's surface is not static; it deforms at different rates and scales in different places. At any one time, the sum of such dynamics controls the volume of the global ocean basin and, therefore, for a fixed volume of seawater, dictates the average sea level worldwide. At the same time, and because both the dynamic Earth surface and the volume of seawater change through time, in combination they also control the multiplicity of local rates of sea-level change we actually observe.

The possibility of large and damaging sea-level rises caused by human-related global warming features prominently in presentations by those who call for urgent action to "stop" global warming, such as former U.S. Vice President Al Gore (Gore, 2006).

Past sea-level positions are measured or inferred from geological evidence. Factual observations regarding modern sea level and its change are traditionally made using tide gauges. Since the early 1990s, modern sea level also has been measurable independently by radar-ranging from satellites.

When data from these sources are analyzed, rates of sea-level change, either rises or falls, are found to vary through time and space (geography), and often quite dramatically over geological time scales. We discuss below several matters relevant to the assertion of both natural and possible human-caused sea-level rise, organizing the discussion into sections that address observations, modeling, mechanisms, and policy. *Inter alia*, we examine historical trends in sea level to see if any recent increase has occurred in global sea level in response to the supposedly unprecedented warming of the planet over the twentieth century; discuss the proposed scenarios whereby either melting ice or a warming ocean might cause sea levels to rise; and consider the important questions of decadal and multidecadal variability in rates of sea-level change, including both accelerations and decelerations of the rate of change.

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Nicholls, R.J., 2011. Planning for the impacts of sea-level rise. *Oceanography* **24**(2): 144–157.

6.2.1.1. Geological studies

Changes in sea level over long periods of time (millions of years) are inferred from geological evidence. By their nature, most such records are of local relative change, and they require correction if they are to be translated into eustatic estimates (e.g., Kominz *et al.*, 1998).

For about the past 3 million years a high-quality proxy record for eustatic sea level is represented by the oceanic oxygen isotope record (e.g., Lisiecki and Raymo, 2006; see Figure 6.2.1.1.1). This curve is based on the measured ratio of two isotopes, ^{16}O and ^{18}O, that are fractionated in seawater and hence vary in the shells of fossil animals that lived in that water in accordance with fluctuations of global ice volume through time. High-resolution (millennial) oxygen isotope curves from all ocean basins and latitudes contain a common signal pattern that has become a standard for subdividing Quaternary time into climatic Marine Isotope Stages (MIS), numbered backwards through time. The present interglacial (termed the Holocene and defined as starting 11,700 years ago) is effectively synonymous with MIS 1.

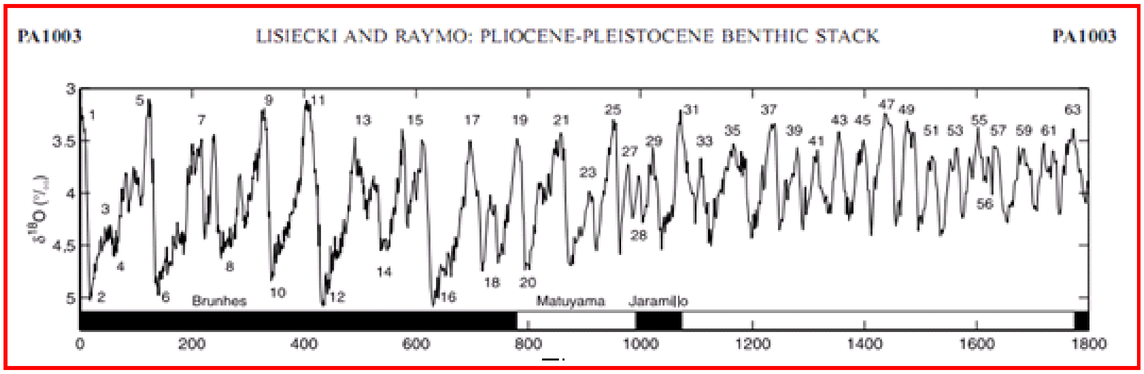

Figure 6.2.1.1.1. Oxygen isotope curve showing the major climatic fluctuations of the last 1.8 million years; numbered peaks indicate Marine Isotope Stages, with even numbers corresponding to ice ages and odd numbers to warm interglacials. A full glacial-interglacial range, say between MIS 12 and MIS 11, represents about 120 m of sea-level change. The apparent anomaly of MIS 3 carrying the designation that otherwise equates to a full interglacial interval stems from the early believe that ice ages were paced by variations in the Earth's 41,000 obliquity cycle. Adapted from Lisiecki, L.E. and Raymo, M.E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic del-^{18}O records. *Paleoceanography* **20**: PA1003. doi: 10.1029/ 2004PA001071.

The last ice age reached its peak about 20,000 years ago, at which time sea level stood at about -120 m with respect to today. Efforts have been made to reconstruct a global sea-level curve for the period since then, based on careful geological sampling and dating of sea-level-related materials such as mangroves or coral reefs. The resulting curve, in Figure 6.2.1.1.2, shows very rapid melting, at rates up to 26 mm/y over short periods between about 15,000 and 10,000 years ago, after which the rate of rise lessens to 1–2 mm/y in the Holocene.

It is important to note glacio-isostatic effects may have distorted or invalidated the key proxy sea-level records that have been used to construct Figure 6.2.1.1.2 and similar post-glacial sea-level curves (Gehrels, 2010). For example, Bowen (2010) has shown tectonic effects have resulted in a range of

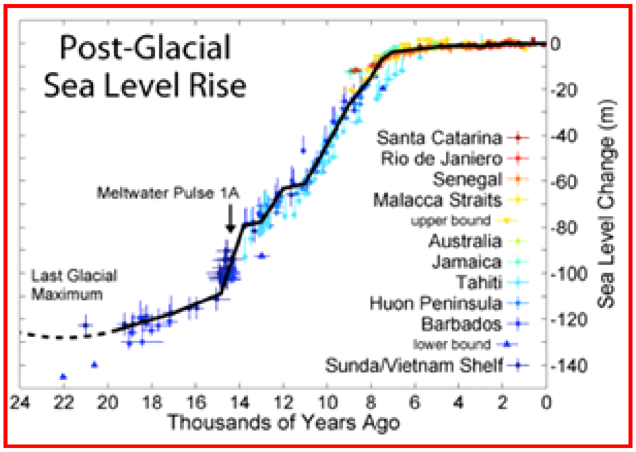

Figure 6.2.1.1.2. Reconstructed global sea-level since the Last Glacial Maximum, 20,000 years ago, based on dated worldwide coral and peat deposits. Adapted from Fairbanks, R.G. 1989. A 17,000 year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342**: 637–642; Toscano, M.A. and Macintyre, I.G., 2003. Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from *Acropora palmate* framework and intertidal mangrove peat. *Coral Reefs* **22**: 257–270.

estimates for sea level during warm interglacial MIS 11, most of which do not support the high +20 m level some previous authors have estimated but instead lie closer to present day sea level. It is the presence of significant regional variations in the timing and shape of the sea-level curve, particularly over the past 7,000 years, that led Gehrels (2010) to suggest "'Eustasy' is therefore merely a concept, not a measurable quantity."

Ignoring these geological perspectives, the first reports by the IPCC claimed human-forced sea-level rise could reach as high as 2–3 m by the year 2100 (Hoffman *et al.*, 1983; Kaplin, 1989). Although subsequent IPCC reports have lowered the sea-level rise estimate to something more realistic, individual authors continue to promulgate potential sea-level rises of 1–2 m or more by 2100 AD, supposedly caused by exceptional melting of ice in the Greenland and Antarctic ice caps (e.g., Rapley, in Doyle, 2007; Rahmstorf, 2007).

Hansen and Sato (2011) claimed sea level will rise 5 m by 2100 AD and proposed an exponential increase in glacier melting would produce a 4 m rise in sea level in the 20-year period from 2080 to 2100, a rate of 200 mm/year. These frenetic estimates are made notwithstanding that the Antarctic ice cap has expanded, not decreased, in the past 20 years (see Chapter 5) and the Greenland ice cap was about the same size as today during the 2.5 °C warmer Holocene Climatic Optimum (Willerslev *et al.*, 2007).

In a number of papers Nils-Axel Mörner (1983, 2004, 2011) has established a maximum possible glacial eustatic rate of change of 10 mm/yr, or 1.0 m/century, derived from the rates that occurred during the glacial eustatic rise after the last glaciation maximum (LGM) of the Last Ice Age at around 20 ka with a sea-level lowstand of about 120 m. The main contribution to the large post-glacial rise in sea level came from melting of the continental ice caps over North America and northwest Europe. a value of 10 mm/yr sets a realistic natural frame for possible maximum rates of modern sea-level rise that might ensue should ice-cap melting quicken.

More generally, it is important to address critically the degree to which sea-level changes on geological timescales can be used to predict future change. Past changes are reconstructed from geologic and geomorphic evidence along coastlines and from inferences drawn about changing ocean geochemistry ($^{18}O/^{16}O$ ratios measured on marine microfossils in cores). These are very different lines of evidence, and interpretation of the geochemical studies is further complicated by shifting isotope ratios being caused not only by temperature, but also by water exchanged between the oceans and ice caps during climate cycling. While the temperature term can be removed for some samples using Mg/Ca measurements, the hydrographic effect remains uncertain. Therefore, while an averaged $\delta^{18}O$ signal of global variability provides an overall indication of the magnitude of glacials and interglacials, as shown in Figure 6.2.1.1.1 above, it is difficult to be confident such data can provide an accurate guide to sea-level variability when differences of at most a few meters are involved for future prediction.

Similar uncertainty presents itself when estimates of lowered sea level and its timing are estimated for the Last Glacial Maximum in order to calibrate sea-level change represented in the $\delta^{18}O$ record. Lowstand estimates range from -130 m at 20,000 yrs ago (Yokoyama *et al.*, 2000) to -120 m 26,000 yrs ago (Peltier and Fairbanks, 2006). These differences may be caused by regional variability (Elderfield *et al.*, 2012), but they make clear the difficulty of acquiring accurate sea-level estimates. Estimates derived from calculating the effects of glacial isostatic readjustment (GIA) after the last ice age, especially for far field locations, are uncertain. Variability in time and space of the water content of the mantle (especially olivine) influences its viscosity, which in turn controls isostatic response and is poorly understood (Jones *et al.*, 2012).

Conclusions

Geological evidence provides an important knowledge framework but seldom offers the accuracy and precision needed to inform estimates in the decimeter to several-meter range likely to apply to near-future sea-level rise. Moreover, projections of sea-level change out to 2100 AD must be considered within the framework set by the known maximum rate of post-glacial sea-level rise, 10 mm/yr (1 m/century). Likely rates of future sea-level rise following melting of the Greenland and/or Antarctic ice caps fall well below this 10 mm/yr figure and probably will lie close to the observed modern level of sea-level rise of ~1.8 mm/yr from all causes.

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Earlier Research

Summarized briefly below are other recent papers that approach the sea-level issue from a geological viewpoint.

- Mörner (2004) noted "prior to 5000–6000 years before present, all sea-level curves are dominated by a general rise in sea level in true glacial eustatic response to the melting of continental ice caps"; given the slowdown of this process thereafter, "sea-level records are now dominated by the irregular redistribution of water masses over the globe ... primarily driven by variations in ocean current intensity and in the atmospheric circulation system and maybe even in some deformation of the gravitational potential surface." With respect to the past 150 years, Mörner reports the mean eustatic rise in sea level for the period 1850–1930 was 1.0–1.1 mm/year, but "after 1930–40, this rise seems to have stopped until the mid-1960s (Pirazzoli *et al.*, 1989; Mörner, 1973, 2000)." Thereafter, with the advent of the TOPEX/Poseidon mission, Mörner notes "the record can be divided into three parts: (1) 1993–1996 with a clear trend of stability, (2) 1997–1998 with a high-amplitude rise and fall recording the ENSO event of these years and (3) 1998–2000 with an irregular record of no clear tendency." Importantly, Mörner concludes "there is a total absence of any recent 'acceleration in sea-level rise" and, therefore, "no fear of any massive future flooding as claimed in most global warming scenarios."

- The PALeo SEA Level Working Group (PALSEA, 2009, 2012) of 32 experienced researchers was convened to examine and summarize the records of recent geological scale sea-level change to provide context for speculations regarding future sea-level rise. With respect to the IPCC's estimate that global warming between 1.1°C and 6.3°C will occur in the twenty-first century, the group points out the last global warming of comparable magnitude occurred during the termination of the last glacial period. That warming consisted of a series of short, sharp steps on millennial to centennial timescales, the magnitude and rate of warming of which are closely analogous to those of the anthropogenic warming predicted to occur over the coming centuries. This comparison immediately rules out any type of exponentially increasing sea-level response, pointing more toward an asymptotic response where sea-level rise is high initially but gradually levels off (Figure 6.2.1.1.3).

Extending the time scale to the 11,700-year Holocene period, the PALSEA team identified rapid warming and eustatic sea-level rise between 9 and 8.5 ka BP and 7.6 and 6.8 ka BP (increases of 1.3 and 0.7 m per century, respectively). Although a "rapid demise of ice sheets in a climate similar to today is certainly a possibility," they note, "an improved understanding of ice sheet dynamics is required before one can conclude that the Greenland or West Antarctic ice sheets will behave in a similar fashion in the future." The PALSEA group noted peak sea levels during the last interglacial period were about 3–6 m above modern sea level at 126 ka BP but attained these highs only "several thousand years after proxy records of temperature reached interglacial levels."

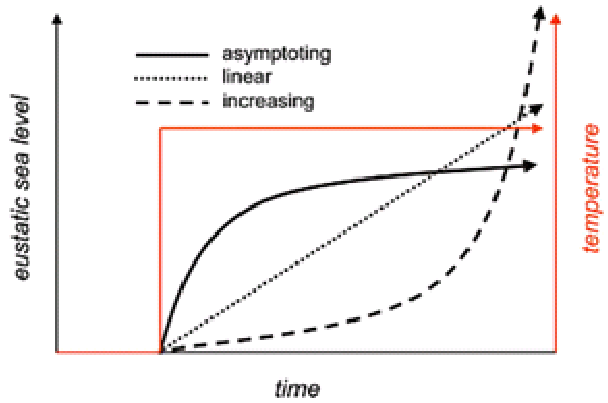

Figure 6.2.1.1.3. Three alternative models for sea-level rise. Adapted from PALSEA, 2009. The sea-level conundrum: case studies from palaeo-archives: *Journal of Quaternary Science* **25**: 19–25.

Overall, if the worst-case warming scenario of the IPCC were actually to occur, the PALSEA scientists conclude the likely sea-level rise would lie between the lower limit of twentieth century sea-level rise (0.12 m per century) and sea-level rise at the conclusion of the last glacial period (1 m per century).

- Yokoyama and Esat (2011) note climate change does not always produce a measurable sea-level response, but when it has, that response was rapid and usually accompanied by shifts in ocean circulation.
- Stanford *et al.* (2011) found the most likely maximum rates of sea-level rise during the post-glacial melting ranged from 13 to 15 mm/y, perhaps peaking at 26 mm/y for short periods (decades at most). The maximum rates of rise occurred in two short bursts, referred to as melt-water pulses, that appear to be linked to breakout floods from large Northern Hemisphere pro-glacial lakes. As no large meltwater lakes exist today, such high rates of rise are unlikely to be repeated.

Conclusions

The conclusions drawn from geological evidence contradict the logarithmically increasing sea-level response assumed by the empirical and semi-empirical models used by the IPCC. Some researchers have used the output of these models to generate alarm by saying currently observed sea-level change is slow only because of a lagged response to temperature forcing; they contend sea-level rise will become progressively faster (10 mm/y or more) in the future. Furthermore, some researchers assume, without justification, that a projected global eustatic sea-level curve is indicative of local or regional sea-level changes.

Natural geological constraints mean predictions of sea-level changes between now and 2100 AD must fall within the frames set by the post-last-glaciation-maximation rates of sea-level rise: less than 10 mm/yr. Any near-future rate of melting of the Greenland and/or Antarctic ice caps is likely to fall well below the rate of the major post-glacial warming.

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6.2.1.2. Tide gauges

Local relative sea level traditionally has been measured at ports using tide gauges, some of which have records extending back to the eighteenth century (see Figure 6.2.1.2.1). These measurements tell us

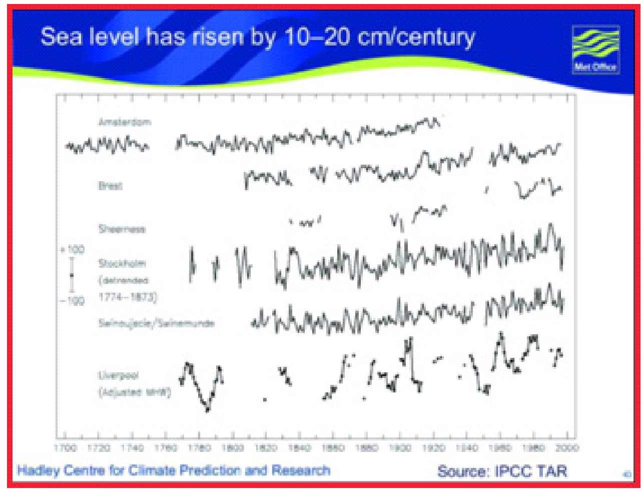

Figure 6.2.1.2.1. Long, northern hemisphere tide gauge records of sea-level change, 1700–2000. Adapted from Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001. 3rd Assessment Report of the IPCC.*

about the change occurring in actual sea level at particular coastal locations, including rises in some places and falls at others. After correcting for any site-specific tectonic or oceanographic-meteorologic distortions of the underlying eustatic sea-level signal, a number of geographically dispersed tide gauge records can be averaged to provide an estimate of the global sea-level curve.

Tide gauges measure water-level oscillations, not merely changes in mean sea level. Various techniques are used to filter out the influence of unwanted oscillations (Pugh, 2004). The tide gauge is constructed in such a way that the instrument gives a limited response to short-duration oscillations such as swell waves and vessel wakes. Numerical techniques are used to extract the oscillations of interest. The analysis generally is optimized to extract tidal constituents, which is not ideal for assessing long-term sea-level changes, particularly since some tidal constituents have periods of years to decades.

After correcting for these factors and for subsidence or uplift, the longer-term tide-gauge records indicate a twentieth century sea-level rise of +1–2 mm/y. Based on these records, the IPCC (2001) estimated an average rate of eustatic rise between 1900 and 2000 of 1.6 mm/y. However, the derivation of such a rate of change is usually achieved by least-squares linear trend analysis. Such calculations are highly sensitive to the start and end points selected for the dataset being considered, and they ignore short-term and multidecadal changes in sea level known to be associated with meteorological and oceanographic oscillations such as ENSO and the Pacific Decadal Oscillation.

Despite the "consensus" adoption of 1.6–1.8 mm/y as the most likely rate of sea-level rise estimated from tide gauge records, Goddard (2013) recently has shown a straight averaging of the trends of the 159 tide gauge records represented in the NOAA tidal database indicates a much lower figure of only 0.7 mm/y, Similarly low rates of 0.5–1.2 mm/y over historic or late Holocene periods also have been reported by several other authors (Burton, 2010; Gehrels and Woodworth, 2013; Miller *et al.*, 2009; Mörner, 2004, 2012).

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Earlier Research

That global average sea level has been rising gently for the past 100+ years has been established by observation. The precise rates of change and the degree to which those rates vary through time remain open questions in the research literature. Some of the many papers that bear on the topic are summarized below.

- Cazenave *et al.* (2003) studied variation in global sea level on interannual to decadal time scales, focusing on the thermal expansion of the oceans and the continental water mass balance. They determined a rate of thermosteric sea-level rise over the previous 40 years of about 0.5 mm/year. They note, however, 1993–2000 analyses of TOPEX-Poseidon altimetry data and the global ocean temperature data of Levitus *et al.* (2000) both yielded rates of rise approximately six times greater than their inferred rate. They interpreted this to mean "an acceleration took place in the recent past, likely related to warming of the world ocean." Other interpretations acknowledged by Cazenave *et al.* are that "the recent rise may just correspond to the rising branch of a decadal oscillation" and "satellite altimetry and in situ temperature data have their own uncertainties and it is still difficult to affirm with certainty that sea-level rise is indeed accelerating." On this second point, Nerem and Mitchum (2001) indicate at least 20 years of satellite altimetry data are necessary to detect an acceleration in sea-level rise).
- Jevrejeva *et al.* (2006) analyzed information in the Permanent Service for Mean Sea Level data-base using a method based on Monte Carlo Singular Spectrum Analysis, designed to remove 2- to 30-year quasi-periodic oscillations to derive nonlinear long-term trends for 12 large ocean regions. These curves were combined to produce the mean global sea level (upper) and rate-of-rise (lower) curves depicted in Figure 6.2.1.2.2. The figure shows no acceleration of sea-level rise since the end of the Little Ice Age around 1860. Jevrejeva *et al.* say "global sea-level rise is irregular and varies greatly over time" but "it is apparent that rates in the 1920–1945 period are likely to be as large as today's." In addition, they report their "global sea-level trend estimate of 2.4 ± 1.0 mm/year for the period from 1993 to 2000 matches the 2.6 ± 0.7 mm/year sea-level rise found [then] from TOPEX/Poseidon altimeter data."
- White *et al.* (2005) compared estimates of coastal and global averaged sea level for 1950 to 2000, confirming earlier findings of "no significant increase in the rate of sea-level rise during this 51-year period." They note several earlier investigators (Douglas, 1991, 1992; Maul and Martin, 1993; Church *et al.*, 2004; Holgate and Woodworth, 2004) similarly concluded the measured rate of global sea-level rise was rather stable over the past hundred years, in contrast to the climate model projections for an increase in rate during the twentieth century.

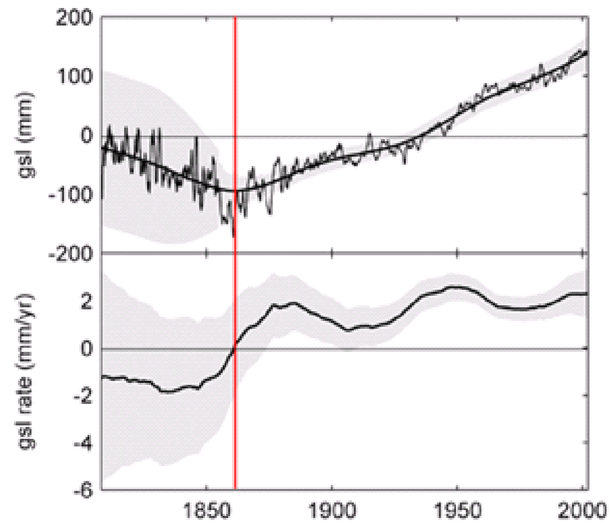

Figure 6.2.1.2.2. Mean global sea level (top), with shaded 95% confidence interval, and mean rate-of-rise (bottom), with shaded standard error interval. Adapted from Jevrejeva, S., Grinsted, A., Moore, J.C., and Holgate, S. 2006. Nonlinear trends and multiyear cycles in sea-level records. *Journal of Geophysical Research* **111**: C09012, doi:10.1029/2005JC003229, 2006.

- Aiming to improve the correction of tide gauge data for vertical substrate motion, Wöppelmann *et al.* (2009) analyzed GPS vertical velocities from a global network of 227 stations between 1997 and 2006. Of the stations they studied, 160 were located within 15 km of an established tide gauge. Assuming land motion is essentially linear over the time span considered, Wöppelman *et al.* used the GPS vertical velocities they derived "to correct for the land motion affecting the tide gauge records to derive absolute (geocentric) changes in sea level." They obtained a global-average rate of geocentric sea-level rise for the past century ranging from 1.55 to 1.61 mm/year, depending on whether one outlier (of 28 individual regions) was included or omitted from their analysis. Wöppelmann *et al.* conclude their result is "in good agreement with recent estimates" such as Church and White (2006; 1.7 mm/yr), Holgate (2007; 1.7 mm/yr), and Leuliette and Miller (2009; 1.5 mm/yr for 2003–2007, using satellite altimetry, Argo, and GRACE gravity observations to estimate the sum of the thermosteric and land ice contributions to sea-level rise).
- Wenzel and Schroter (2010) used a method of neural net analysis in a novel attempt to resolve problems such as tectonic movement or missing data at individual stations. Using 56 tidal stations with at least 50 years of data each, the researchers first corrected the data for substrate movement up or down. The training data used for the neural net were three sets of altimetry data for recent decades, and all three results were shown. Wenzel and Schroter found no net trend in sea level for the South Atlantic and tropical Indian Oceans and a net decline for the Southern Indian Ocean. The Pacific Ocean showed an approximate 70-year oscillation in sea level that correlates (with lag) with the Pacific Decadal Oscillation, while the Atlantic showed cycles of 23 and 65 years. Overall, ocean basin changes showed lagged correlations with the PDO and Southern Annular Mode indices.

  Averaging these results over the globe as a whole, Wenzel and Schroter arrived at a linear upward sea-level trend of 1.56 mm/year with no sign of recent acceleration. Their results agree with those of Hagedoorn *et al.* (2007) of 1.46 mm/year and Wöppelmann *et al.* (2009) of 1.61 mm/year, as well as other recent studies that give only slightly higher values, around 1.7–1.8 mm/year.
- In another novel approach, Church *et al.* (2011) compared results from tide gauge and satellite altimeter measurements. They based their approach on solving Earth's sea-level and energy budgets together in a consistent manner, using the latest available data for the period 1972–2008. They found good agreement between the mean annual sea-level and energy budgets, as illustrated in Figure 6.2.1.2.3. They observed, "from 1972 to 2008, the observed sea-level rise [1.8 ± 0.2 mm/year from tide gauges alone and 2.1 ± 0.2 mm/year from a combination of tide gauges and altimeter observations] agrees well with the sum of energy budget contributions (1.8 ± 0.4 mm/year) in magnitude and with both having similar increases in the rate of rise during the period."

Conclusions

These studies generally suggest the twentieth century has seen a steady rise in global sea level of between about 1.4 and 1.8 mm/yr, albeit modulated at a decadal or multidecadal scale.

This raises an obvious question: If the late twentieth century global warming was as extreme as the IPCC claims it has been, why can it not be detected in global sea-level data? The effects of the warming that led to the demise of the Little Ice Age—which the IPCC contends should have been considerably less dramatic than the warming of the late twentieth century—are readily apparent from the work of Jevrejeva *et al.* shown in Figure 6.2.1.2.2 above; they show a broad similarity in sea-level

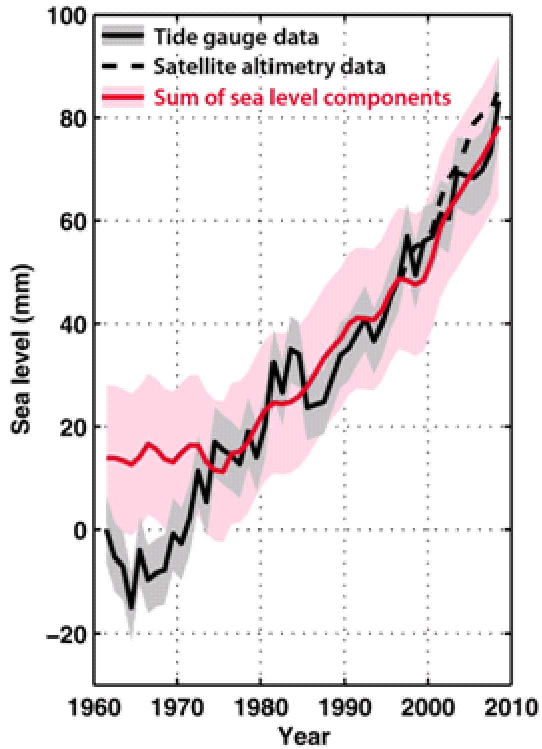

Figure 6.2.1.2.3. Mean global sea level vs. time, as derived from tide gauge data, satellite altimetry data and summing of the individual contributory components to sea level rise. Adapted from Church, J.A., White, N.J., Konikow, L.F., Domingues, C.M., Cogley, J.G., Rignot, E., Gregory, J.M., van den Broeke, M.R., Monaghan, A.J., and Velicogna, I. 2011. Revisiting the earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters* **38**: 10.1029/ 2011GL048794.

response throughout the 150-year-long post-LIA period, with a lessening of the rate of rise for the 1960s through the 1980s.

Similarly, although the rate of increase in atmospheric carbon dioxide levels grew dramatically just after 1950, shifting from a 1900–1950 mean rate of rise of 0.33 ppm/year to a 1950–2000 mean rate of rise of 1.17 ppm/year, the mean global sea-level rate of rise did not trend smoothly upwards after 1950.

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6.2.1.3. Satellites

Since the early 1990s, sea-level measurements have been made by microwave radar and laser ranging from various orbiting satellites, including the U.S. TOPEX-Poseidon, the European Remote-Sensing Satellite (ERS), Geosat Follow-On (GFO), EnviSat, and Jason series. Situated in polar geostationary orbit, these satellites are able to make repeat measurements of the exact distance to the sea surface at locations across the globe over cycles varying between three and 35 days as Earth rotates below the satellite (see Figure 6.2.1.3.1).

Thus, like tide gauge measurements although with almost complete coverage between 66° N and 66° S, satellites measure changing sea-level heights through time and therefore provide many records of sea-level change at different places (see Figure 6.2.1.3.2), which subsequently can be averaged into an estimate of global sea-level change over a specified period (Figure 6.2.1.3.3).

Averaging the repeat measurements for each location removes the effects of tides and waves. The nominal accuracy of about +/- 100 mm can be improved to about +/- 40 mm by averaging 10-day-separated repeat measurements, or +/- 20 mm for monthly averages, at particular locations (Leuliette and Willis, 2011; Leuliette, 2012). This accuracy is not fully secure because we lack knowledge of the benchmark reference frame for the shape of Earth, the geoid, as well as other uncertainties introduced by the need for corrections for orbital drift and decay and for the stitching together of records from different successive satellites.

Both satellite and tide gauge data are used to estimate the rates of sea-level change over time by fitting a statistical model to the data, usually a linear model. The overall gradient of the resulting model fit is the estimate of the rate of sea-level change. There are complications with undertaking this type of analysis, including the errors associated with each data point and serial correlation of the measurements.

For time-series of sea-level data, successive measurements are often correlated with preceding data because there are repeating patterns, and as sea-level changes, the next measurement is more likely to change in the same direction than in the opposite direction. This increases the uncertainty in the estimates of the slope and is not always accounted for. Further, the slope is usually quoted to a greater precision than the data (e.g., 0.1 mm for satellite data with an accuracy of about 20 mm), which can give a misleading impression of the accuracy of the estimated rate of sea-level rise.

It is important to note satellites and tide gauges do not measure quite the same thing. Tide gauges measure relative to a fixed land benchmark (usually the mean tide level), while satellites measure relative to a mathematical model of the shape of Earth's gravity field (geoid) that is not well characterized and varies over time. Accordingly, a component of satellite "sea-level change," perhaps as much as 50 percent, actually results from geoid changes.

Given these uncertainties, it is not surprising to find the satellite measurements yield an estimate of the rate of global sea-level change that differs from the tide gauge record, indicating an almost doubled rate of rise of more than 3mm/y. The main cause of this discrepancy is likely geoid inaccuracy (see Section 6.2.1.8 below).

Our discussion so far has centered on data collected and processed by NOAA's U.S.-based satellite fleet as presented at the NOAA Laboratory for Satellite Altimetry Web site (NOAA LSA, 2012) (Figure 6.2.1.3.3). But another problem with satellite-borne measurements is that significant differences occur among the sea-level curves reconstructed using different sensors and by different research groups.

For the period 2002–2012, independent sea-level measurements were conducted using the European Space Agency's (ESA) ENVISAT satellite. Until shortly before its failure in 2012, the 2004-onward ENVISAT record (Figure 6.2.1.3.4) persistently displayed a lower rate of sea-level rise than that indicated by U.S. measurements (Figure 6.2.1.2.3).

In June 2012, a new posting of an extended (back to 2002) ENVISAT sea-level curve was made (see Figure 6.2.1.3.5). For the new curve, corrections were made by reprocessing data and incorporating an unspecified "instrumental correction" of +2 mm/y. These corrections increased the "measured" ENVISAT rate of sea-level rise from 0.76 mm/y to 2.33 mm/y, bringing the ESA's results more in line with those of NOAA. Meanwhile, since early 2011, the NOAA data themselves had been adjusted toward a higher rate of sea-level rise by the addition of a +0.3 mm/y glacial isostatic (GIA) adjustment.

It is of course entirely possible the calibration and correction procedures used for any particular satellite instrument package are in error, and that later data adjustments are therefore justified when this is discovered—and perhaps especially so given that

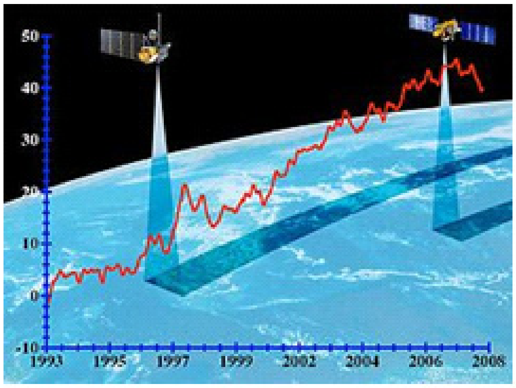

Figure 6.2.1.3.1. Graphic depicting NOAA satellite collecting sea-level data using radar altimetry, 1993–2008. Adapted from NASA.

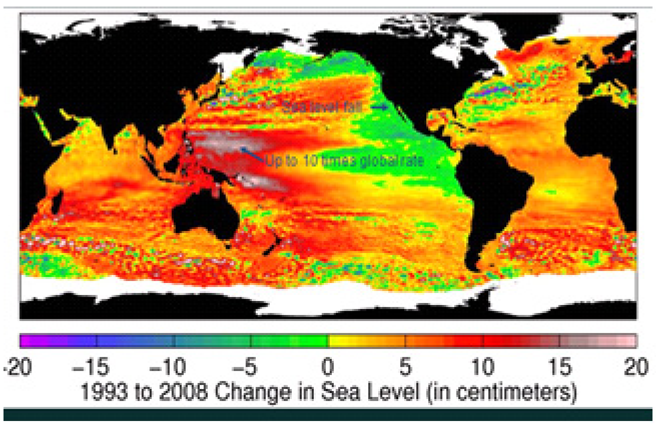

Figure 6.2.1.3.2. Sea-level rise is spatially very non-uniform. Synoptic global map of rate of sea-level change 1993-2008, as measured by radar altimetry. Adapted from NOAA.

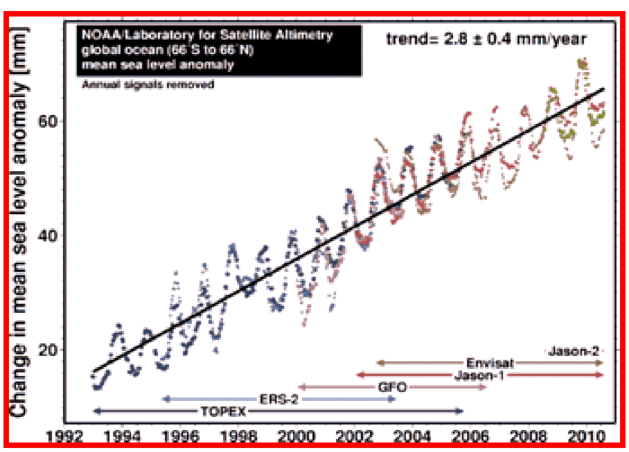

Figure 6.2.1.3.3. NOAA satellite altimetry, global sea-level change since 1992. Dataset composite, collected from successive satellites (coded in color) and plotted monthly.

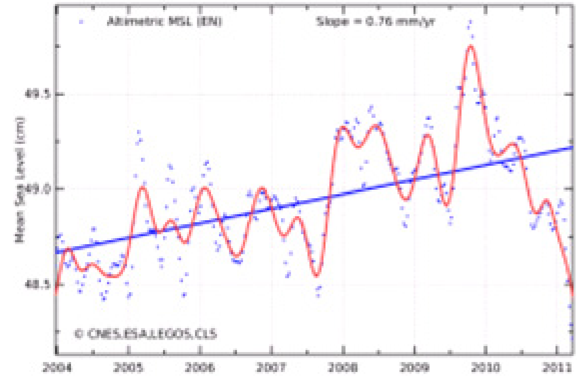

Figure 6.2.1.3.4. ENVISAT sea-level record with fitted trend line of +0.76 mm/y, 2002–2012. Adapted from Watts, A. 2012. ENVISAT's satellite failure launches mysteries. http://wattsupwiththat.com/2012/04/12/envisats-satellite-failure-launches-mysteries/.

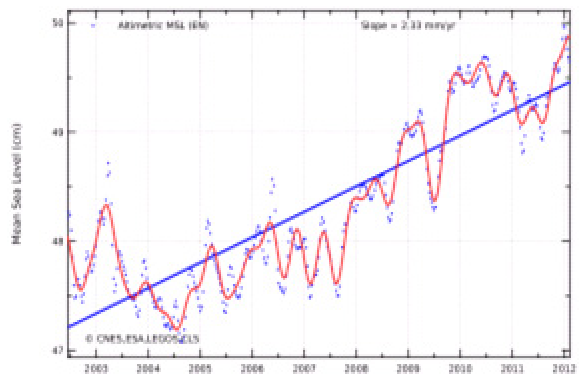

Figure 6.2.1.3.5. Arbitrarily adjusted ENVISAT sea-level record with fitted trend line of +2.33mm/y, 2004-2012 (after Watts, 2012).

ENVISAT persistently had been recording lower rates of rise than other satellites. But it is also disturbing that such adjustments nearly always seem to result in *increases* in the rate of sea-level rise determined; given a significant number of different arbitrary corrections, one might expect about one-half would increase and one-half lessen the rate of rise.

Government science agencies around the world often argue for "correction" of data to bring them into line with a preconceived result. New Zealand's crown research agency, the National Institute of Water and Atmospheric Research (NIWA), has suggested all New Zealand tide gauge records should have a GIA adjustment of +0.4 mm/y to bring the regional Southwest Pacific rate of sea-level rise into line with the global estimate of 1.8 mm/y. This contradicts the recommendation that sea-level rise should be assessed regionally and not in terms of a poorly constrained global average (Gehrels, 2010).

Conclusions

To the extent satellite altimetric measurements continue to return rates of sea-level rise greater than 2 mm/yr, and especially greater than 3 mm/yr, the results must remain suspect, because such high rates conflict with the well-established twentieth century rates of 1–2 mm/yr calculated from tide gauge data.

The mismatch between satellite and tide gauge records was addressed by Wunsch *et al.* (2007), who point out "the widely quoted altimetric global average values may well be correct, but the accuracies being inferred in the literature are not testable by existing in situ observations." Using modeling, they derived an alternative global mean sea-level change estimate for 1993–2004 "of about 1.6 mm/y, or about 60% of the pure altimetric estimate, of which about 70% is from the addition of freshwater." This rate of change is very close to that indicated by the tide gauge records.

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Earlier Research

The reconstruction of sea-level curves from satellite altimetric data remains a vigorous field of study. We summarize below three important earlier papers in the field.

- Church *et al.* (2004) used TOPEX/Poseidon satellite altimeter data to estimate global empirical orthogonal functions, which they combined with historical tide gauge data to estimate monthly distributions of large-scale sea-level variability and change over the period 1950–2000. They estimated the globally averaged sea-level rise for the last half of the twentieth century at 1.8 ± 0.3 mm/year, a figure in close agreement with tide gauge estimates. In addition, they note "decadal variability in sea level is observed, but to date there is no detectable secular increase in the rate of sea-level rise over the period 1950–2000." They conclude there was no increase in the rate of sea-level rise for the entire twentieth century, citing the work of Woodworth (1990) and Douglas (1992).
- Cazenave and Nerem (2004) seem to dismiss the caution shown by Cazenave *et al.* (2003) in claiming "the geocentric rate of global mean sea-level rise over the last decade (1993–2003) is now known to be very accurate, 2.8 ± 0.4 mm/year, as determined from TOPEX/Poseidon and Jason altimeter measurements." Placing faith in this result leads them to note "this rate is significantly larger than the historical rate of sea-level change measured by tide gauges during the past decades (in the range of 1–2 mm/year)." Nonetheless, they concede "the altimetric rate could still be influenced by decadal variations of sea level unrelated to long-term climate change, such as the Pacific Decadal Oscillation, and thus a longer time series is needed to rule this out."

Importantly, because it is often ignored, Cazenave and Nerem also note satellite altimetry reveals a "non-uniform geographical distribution of sea-level change, with some regions exhibiting trends about 10 times the global mean" (see Figure 6.2.1.3.2). Regional differences are also highlighted by the fact that "for the past 50 years, sea-level trends caused by change in ocean heat storage also show high regional variability." Cazenave and Nerem report "these [satellite altimetric] tools seem to have raised more questions than they have answered."

- Carton *et al.* (2005) note "recent altimeter observations indicate an increase in the rate of sea-level rise during the past decade to 3.2 mm/year, well above the centennial estimate of 1.5–2 mm/year," noting further "this apparent increase could have resulted from enhanced melting of continental ice or from decadal changes in thermosteric and halosteric effects." Using a new eddy-permitting Simple Ocean Data Assimilation version 1.2 reanalysis of global temperature, salinity, and sea level for the period 1968–2001, they determined "the effect on global sea-level rise of changing salinity is small except in subpolar regions." They also found warming-induced steric effects "are enough to explain much of the observed rate of increase in the rate of sea-level rise in the last decade of the twentieth century without need to invoke acceleration of melting of continental ice."

It follows, as determined also by Lombard *et al.* (2005), that the high rate of global sea-level rise observed over the past decade is probably a transient result of the global ocean's thermal behavior. Consequently, and in harmony with the findings of Levitus *et al.* (2005) and Volkov and van Aken (2005), there is no need to invoke the melting of land-based glacial ice to explain the observed recent increase in global sea level.

Conclusions

Estimates of sea-level change made using satellite-collected data remain problematic because, among other reasons, they are heavily dependent on the accuracy of a GIA adjustment that lacks independent verification (Houston and Dean, 2012). Summarizing comparisons between the tide gauge and satellite altimeter studies, Houston (2013) concludes, "[It] cannot be determined yet whether the greater trend measured by the altimeters and tide gauges from 1993 to 2011 is the leading edge of a sustained rise or a fluctuation similar to others that have occurred in the twentieth century."

As Wunsch *et al.* (2007) noted:

> At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology. The most urgent job would appear to be the accurate determination of the smallest temperature and salinity changes that can be determined with statistical significance, given the realities of both the observation base and modeling approximations. Both systematic and random errors are of concern, the former particularly, because of the changes in technology and sampling methods over the many decades, the latter from the very great spatial and temporal variability. It remains possible that the database is insufficient to compute mean sea-level trends with the accuracy necessary to discuss the impact of global warming—as disappointing as this conclusion may be. The priority has to be to make such calculations possible in the future.

Establishing the credibility of satellite-borne altimetric sea-level measurements awaits the launch of NASA's new GRASP satellite or development of some other mechanism whereby the accuracy of geoid models can be improved.

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6.2.1.4. Short-term, decadal and multidecadal dynamic variability

Sea-level changes on a short-term, decadal, or multidecadal scale are driven by changes in the heat energy or dynamics of the ocean system (see, e.g., Figure 6.2.1.4.1; similar results were achieved by Fu *et al.*, 1987). These include the effects of spinning up or slowing down major current gyres and the effects of established climatic oscillations such as ENSO (El Niño-Southern Oscillation), the PDO (Pacific Decadal Oscillation), and the SAM (Southern Annular Mode). Sea-level change forced by such mechanisms is generally of low magnitude compared with geological time-scale changes (centimeters to a meter or two only) but can operate at rates as high as 5–10 mm/y.

Another important cause of shorter-term changes in sea level is fluctuation in the energy balance of the ocean, which leads to heating or cooling of the ocean; i.e., thermosteric sea-level change. Fluctuations in sea level have been linked to sunspot cycles (Currie, 1976) and longer-term solar effects (van der Schrier *et al.,*2002). After a phase of warming, expansion, and steric sea-level rise during the late twentieth century, ocean cooling has led to steric sea-level fall since 2002 (DiPuccio, 2009; Loehle, 2009).

Kolker and Hameed (2007) have shown short-term, non-tidal, local sea-level variability is much greater than the magnitude of long-term trends. The cause of this variability is partly unknown, but it includes the effects of storms, winds, floods, wind-driven Rossby waves,[1] shifts in major ocean currents, volcanic heating, and meteorological phenomena (ENSO, PDO).

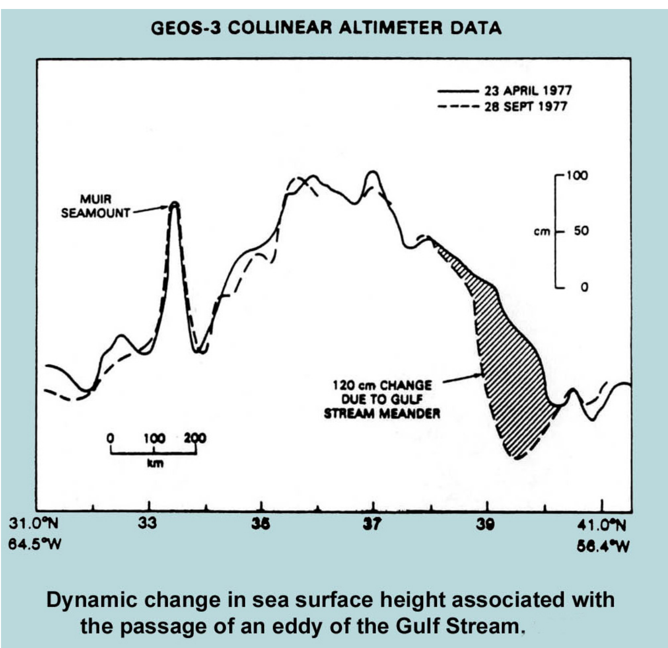

Figure 6.2.1.4.1. Dynamic changes in sea surface height associated with the passing of an eddy of the warm water Gulf Stream, 1977. Adapted from Douglas, B.C., Cheney, R.E., and Agreen, R.W. 1983. Eddy energy of the Northwest Atlantic and Gulf of Mexico determined from GEOS 3 altimetry. *Journal of Geophysical Research: Oceans* **88**(C14): 9595–9603. doi:10.1029/JC088iC14p09595.

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[1] Oceanic Rossby waves travel from east to west under the influence of the shape and rotation of the Earth. They have dimensions of many hundreds of km horizontally but only displace the sea surface by a few cm. Nonetheless, Rossby waves transmit energy and redistribute momentum, thereby exerting effects on the intensity of ocean currents and affecting climate.

Earlier Research

Other papers that have identified short-term sea-level change signals include the following:

- Careful inspection of long historical tide gauge records identifies subtle decadal and multidecadal modulations on the twentieth century long-term rising trend (Marcos *et al.*, 2012). Twentieth century sea-level rise has imprinted on it a rhythmic pattern represented by successive periods of increasing and then decreasing rates of rise.
- In an analysis of high-quality tidal records selected worldwide, Holgate (2007) found a background average rate of sea-level rise of 1.6 mm/y (horizontal black line in Figure 6.2.1.4.2) with regular 20-year-long fluctuations of about -2 mm/y to +5 mm/y. Global sea level actually fell in the 1920s, 1940s, 1960s, 1980s, and around 2000.

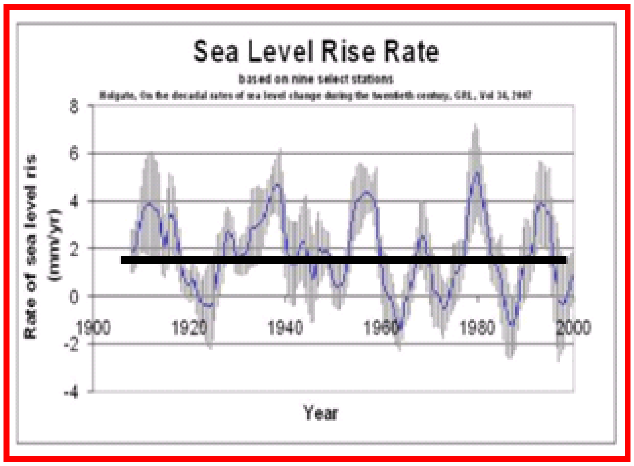

Figure 6.2.1.4.2. Rate of sea-level rise, 1910–2000, based upon analysis of high-quality tide gauge records. Note the average rate of rise (thick black line) of 1.6 mm/y. Note also the presence of fluctuations of rate of between about -2 and +5 mm/y on a decadal to multi-decadal scale, including periods of falling sea-level in 1920, 1940, 1960, 1980 and 2000. Adapted from Holgate, S. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

- Zhang and Church (2012) made a detailed study of interannual and decadal variability in Pacific Ocean sea-level trends. Noting "on a regional scale, such a signal [of anthropogenic change] is mixed with that due to natural climate variability," they set out to separate the natural and anthropogenic signals. This problem has become especially serious since the launch of the TOPEX/Poseidon altimeter, which has encouraged many researchers to report essentially meaningless linear trends in sea-level rise over time spans ranging from a ridiculously short three years to a still-inadequate 18 years.

  Zhang and Church used continuous near-global altimeter measurements since 1993 to attempt to separate interannual and decadal sea-level variability in the Pacific from the long-term background sea-level trend. Their results show "the decreasing regional sea level in the eastern equatorial Pacific is mainly associated with the Pacific Decadal Oscillation" and "for those island countries in the western tropical Pacific and especially low-lying atolls, the high rate of sea level rise over the altimeter era has a significant component associated with natural variability." They conclude using altimeter-based trends as a reference for future climate change projections "needs to be treated with caution as regional sea level linear trends derived over the short altimeter era can be greatly affected by low-frequency climate variability."

Conclusions

Much short- and medium-term sea-level variability is driven by meteorological and oceanographic processes that redistribute water and heat and dictate the ocean response to atmospheric pressure. For environmental management purposes, the dominance of these processes means sea-level changes should be assessed at local or regional scales, not globally.

The presence of decadal and multidecadal fluctuations does not change the general conclusion from tide gauge data that sea level has been rising by an average of about 1.7 mm/year over the twentieth century. However, the presence of these oscillations has a significant effect on the usefulness of linear sea-level trends determined from datasets shorter than the 60-year period of one PDO cycle. Unless such trends are corrected to take into account the position the data they are based on occupies in the longer-term cycle, they are of little value for either scientific or environmental management purposes.

The pitfall is especially great when shorter periods of time are used to infer an acceleration of sea-level rise has occurred (e.g., Merrifield *et al.*, 2009; Sallenger *et al.*, 2012), because that acceleration might be due entirely to the fortuitous position within the 60-year cycle of the data studied (Chambers *et al.*, 2012). Chambers *et al.* state, "one should be cautious about computations of acceleration in sea level records unless they are longer than two cycles of the oscillation."

Natural decadal and multidecadal changes must be taken into account during any projection of future sea levels, yet it is only very recently that scientists have begun to incorporate such changes into their sea-level models.

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6.2.1.5. Acceleration of sea-level rise

Rates of sea-level change are periodic on decadal and longer time scales. For that reason, linear regression though eustatic data is an unreliable technique with which to establish long-term sea-level trends for use in environmental management. Accurate portrayal of any long-term ocean-heating (steric) sea-level rise, putatively due to human influence, is possible only after short-term periodic sea-level behavior has been identified and the records adjusted to account for it.

The important question is not, "is the long-term sea level rising?" Geological, tide gauge, and satellite records all agree it is and, other things being equal, will continue to do so. Instead, to ascertain if rates of sea-level rise are increasing due to human influence we should ask "is sea-level rise accelerating?" The answer to that question is no.

The IPCC (2001) wrote "no significant acceleration in the rate of sea-level rise during the 20th century has been detected." In 2007 it noted "global average sea-level rose at an average rate of 1.8 [1.3–2.3] mm per year over 1961 to 2003. The rate was faster over 1993–2003: about 3.1 [2.4–3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear." This interpretation was based on a comparison of satellite altimetry data, which started in 1991, and tide gauge data. As discussed above (6.2.1.3), the satellite data estimate a higher rate of sea-level rise than do tide gauge data (Wunsch *et al.,*2007), so this result is unsurprising and does not provide evidence of acceleration.

Subsequently, many authors have tested directly for accelerated rise using regional tide gauge datasets. For example, Hannah and Bell (2012) analyzed four 100-year long records from New Zealand's four biggest ports (see Figure 6.2.1.5.1) and found no acceleration beyond the average linear rate of rise of 1.8 mm/yr.

Watson (2010) analyzed the three longest sea-level records (more than 100 years) available in Australasia, from Fremantle, Sydney, and Auckland. The average rates of sea-level rise exhibit by these sites since 1940 are 1.6, 0.4, and 1.2 mm/y, respectively, but all three sites show deceleration over the later parts of the twentieth century rather than acceleration (see Figure 6.2.1.5.2). Other authors also have provided evidence for a slowing rate of sea-level rise during the twentieth century, including Hannah (1990; 2004), Houston and Dean (2011, 2012), Boretti (2012a, b), and Gehrels *et al.* (2012). Woodworth *et al.* (2009) reviewed the available reconstructions for the twentieth century and concluded sea-level rise accelerated around 1920–1930 and decelerated around 1960.

Holgate and Woodworth (2004) derived a mean global, rather than regional, sea-level history using 177 coastal tide gauge records for 1955–1998. Extending that record back in time for another 50 years, Holgate (2007) analyzed nine long high-quality records from locations around the world (New York, Key West, San Diego, Balboa, Honolulu, Cascais, Newlyn, Trieste, and Auckland). The mean sea-level curve for these locations over the 1955–1998 period was compared with the mean curve of the much larger set of 177 stations to establish whether the mean nine-station record would provide a reasonable representation of global sea-level history for the longer period from 1904 to 2003. Holgate concluded, "a few high quality records from around the world can be used to examine large spatial-scale decadal variability as well as many gauges from each region are able to [do]."

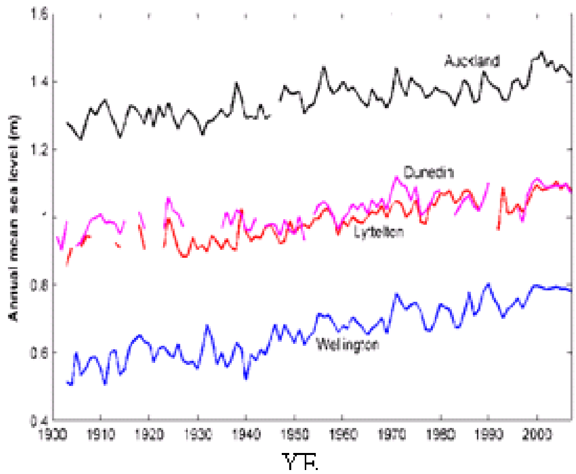

Figure 6.2.1.5.1. 100 year-long tide gauge records from four NZ ports (Auckland, Dunedin, Lyttleton and Wellington), showing a progressive, irregularly varying sea-level rise at an average background linear rate of 1.8 mm/yr. These rates of sea level change are similar to the world average rise as estimated from a global network of similar tide gauges. Adapted from Hannah, J. and Bell, R.G. 2012. Regional sea-level trends in New Zealand: *Journal of Geophysical Research* **117**: C01004–C01004.

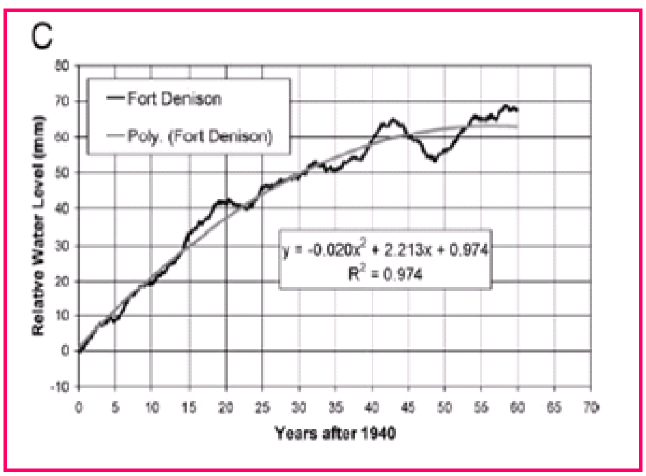

Figure 6.2.1.5.2. Sea-level curve for Sydney Harbour (Port Denison) since 1940, with fitted polynomial curve of decelerating nature. Adapted from Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea-level rise around mainland Australia? *Journal of Coastal Research* **27**: 368–377.

Holgate thereby was able to provide a best-estimate representation of the 1904–2003 mean global sea-level history of the world. This, like Jevrejeva *et al.*'s (2006) similar reconstruction based on a larger tide gauge dataset, showed both multidecadal variations and an overall declining trend (see Figure 6.2.1.5.3). He calculated the mean rate of global sea-level rise was "larger in the early part of the last century (2.03 ± 0.35 mm/year 1904–1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954–2003)." In other words, global sea-level rise has been decelerating since the mid-twentieth century.

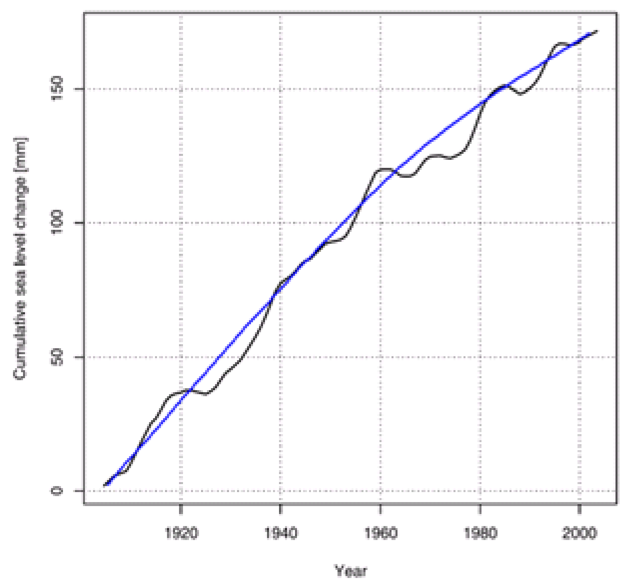

Figure 6.2.1.5.3. Cumulative increase in mean global sea level (1904-2003) derived from nine high-quality tide gauge records from around the world. Adapted from Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. *Geophysical Research Letters* **34**: L01602, doi: 10.1029/2006GL028492, 2007.

The only recent authors who claim to have detected recent acceleration in the rate of sea-level rise are Church and White (2006, 2011). Their earlier paper was based on merging short-term satellite altimetry with the long-term tide gauge records, a hazardous statistical exercise. The combined dataset was produced using a statistical model that matched adjusted tide gauge data and satellite measurements during the period of overlap, and then used that match to reconstruct past sea levels in an attempt to correct for the sparse spatial distribution of older tide gauge data. Church and White (2011) identify acceleration of the long-term sea-level record around 1930 followed by a deceleration around 1960. They also depict the short-term sea-level rise rate was faster at the end of the twentieth century than the long-term rate.

Only broad summaries of the Church and White (2006, 2011) methodologies have been published and their results should be looked upon with caution. Comparison between the earliest version and most recent version of their work indicate pre-satellite sea-level data change as additional satellite data become available. This occurs because the statistical model underlying the merging is changing with the addition of further overlapping data (Church and White, 2011). Furthermore, break point and other statistical analyses indicate a significant change in the underlying characteristics of the data around 1992 (Chambers *et al.,*2012), implying there was a fundamental change in sea-level processes then or the satellite data behave differently than the tide gauge data, as suggested by Wunsch *et al.* (2007) and Domingues *et al.* (2008). The presence of decadal and 60-year-long fluctuations in rates of sea-level change (Holgate, 2007; Chambers *et al.*2011) and brevity of the satellite altimetric record (6.2.1.3, above) suggest it is too soon to use the satellite data as a reliable test for acceleration in late twentieth century sea-level rise.

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Earlier Research

Several other recent papers bear on the question of an accelerated rate of sea-level rise and are briefly summarized below.

- Rahmstorf *et al.* (2012) compared Church and White (2006; 2011) and Jevrejeva *et al.* (2008) with three earlier reconstructions (Gornitz and Lebedeff 1987; Trupin and Wahr 1990; and Holgate and Woodworth 2004) of global sea level, finding general agreement among the analyses that sea-level rise began to accelerate in or before the nineteenth century (Jevrejeva, 2008), although there are very few tide gauge records extending back to the eighteenth century to better secure that result.

  The reconstructions used different sets of tide gauges and different methodologies, including different corrections applied to the data. These corrections include adjustments for local data shifts and corrections for the inverse barometric effect[2] and seasonal effects. Most importantly, the isostatic (GIA) corrections have changed over time as successively newer models of crustal deformation have been calculated, in which regard Houston and Dean (2012) found the predicted GIA was poorly correlated with the GIA measured by continuous GPS, with no systematic pattern of deviations. It should not be surprising there are significant differences as well as similarities between the datasets, and those differences will affect the detection of long-term changes in the rate of sea-level rise.

- Boretti (2012a) analyzed data from the TOPEX and Jason series of satellite radar altimeters to test for recent changes in the rate of sea-level change. He reports the average rate of sea-level rise over the almost 20-year period of radar altimeter observations is 3.164 mm/yr (see Figure 6.2.1.5.4), which if held steady over a century would yield a mean global SLR of 31.64 cm, a little more than the low estimate for 2100 made by the IPCC. Boretti also finds that rather than accelerating, the rate of sea-level rise over the measurement period is decelerating at a rate of -0.11637 mm/yr^2 and this deceleration is itself reducing at a rate of -0.078792 mm/yr^3.

  Boretti notes the deceleration of sea-level rise over the past ten years "is clearly the opposite of what is being predicted by the models," especially as the reduction has been even more pronounced over the past five years. He further notes, "in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the sea level rise must be almost

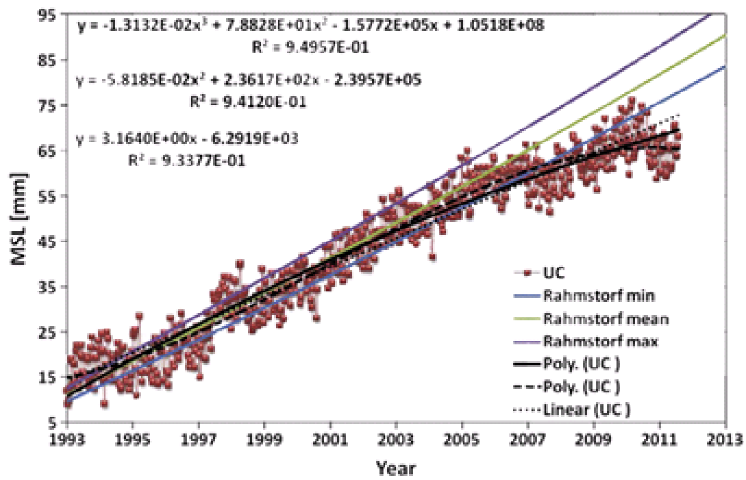

Figure 6.2.1.5.4. Comparison of MSL predictions from Rahmstorf (2007) with measurements from the TOPEX and Jason series. Boretti (2012a), who states in the figure caption that "the model predictions [of Rahmstorf, 2007] clearly do not agree with the experimental evidence in the short term." Adapted from Boretti, A.A. 2012a. Short term comparison of climate model predictions and satellite altimeter measurements of sea levels. *Coastal Engineering* **60**: 319–322.

11 mm/year every year for the next 89 years." A rate of rise of 11 mm/yr has not been achieved once in the past 20 years; rates that fast have been experienced only during the full flush meltwater pulses during deglaciation. The average rise of 3.164 mm/yr found by Boretti is only 20 percent of the sea-level rise needed for the prediction of a one meter rise by 2100 to be correct.

- Boretti (2012b) reports the Australian government has said mass relocation of citizens will be required in the near future in response to "floods … due to the rise of sea levels resulting from increased carbon dioxide emissions." Government maps published for Sydney indicate 0.5, 0.8, and 1.1 meter rises in sea level. Boretti assesses the degree to which such alarm is justified and reports "the worldwide average tide gauge result obtained considering all the data included in the Permanent

[2] In the open ocean, sea level tends to rise/fall 10 mm for every 1 hPa decrease/increase in atmospheric pressure. Because there are interannual and longer fluctuations in mean pressure at sea level, sea level fluctuates in parallel in response.

Service for Mean Sea Level data base show a modest sea level rise and about zero acceleration." He also notes "the Fort Denison, Sydney tide gauge result shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result."Similarly, "the Fremantle tide gauge result, the only other tide gauge operational in Australia over more than a century, shows the same modest sea level rise and about zero acceleration in perfect agreement with the worldwide result and the result of Sydney."Finally, he reports "the other tide gauges operational along the coastline of Australia over shorter time scales of 30 to 40 years on average also show the lack of any acceleration component in the rate of rise of sea levels."

Summarizing his findings, Boretti concludes the "rise of sea level in the bay of Sydney by 2100 is therefore more likely less than the 50 mm measured so far over the last 100 years, rather than the meter [1000 mm] predicted by some models."

- The Australian National Tidal Centre claimed 16 stations with 17 years of record showed a rate of sea-level rise of 5.4 mm/yr. Mörner and Parker (2013) reviewed the same records and found rates of sea-level rise average just 1.5 mm/yr, with no acceleration over recent years.

Conclusions

In its 2007 report, the IPCC projected global sea level was likely to rise somewhere between 18 and 59 cm by 2100. Since then, several model-based analyses have predicted much higher sea-level rise for the twenty-first century, even exceeding 1 meter in some cases (e.g., Rahmstorf, 2007; 2010).

In contrast, multiple careful analyses of tide gauge records by different research teams make it clear the acceleration of sea-level rise proposed by the IPCC and its scientists does not exist. Most records show either a steady state of rise or a deceleration during the twentieth century, both for individual records and for globally averaged datasets. In addition, and though only about 20 years long, the satellite radar altimeter dataset also records a recent decelerating rate of rise (Boretti, 2012a).

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6.2.1.6. Atolls

The assertion that Pacific coral islands are being swamped or "drowned" by rising sea level, thus creating thousands of "climate refugees," retains its hold over many environmentalists, although a London High Court judgment in 2007 against Al Gore found the claim to be untrue (Burton, 2007). Relentless media attention to the matter has ensured it remains in the public eye, with the Tuvalu Islands (Funafuti) receiving the most attention.

Charles Darwin was the originator of the modern theory of coral island and atoll formation (Darwin, 1842) (see Figure 6.2.1.6.1). He speculated when a new volcano erupts above sea level in the tropical

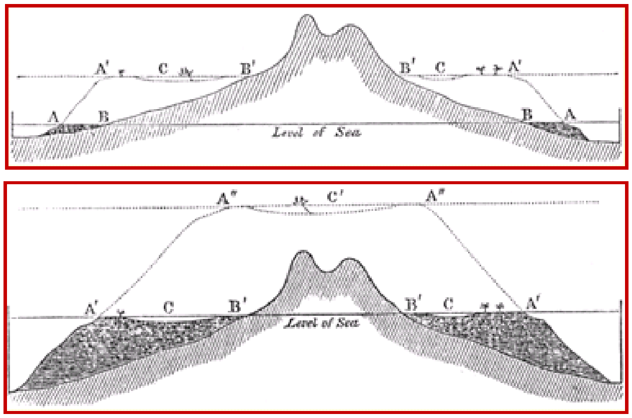


Figure 6.2.1.6.1. The formation of atolls by coral growth around a sinking volcanic island. Adapted from Darwin, C. 1842. *The Structure and Distribution of Coral Reefs.* London, Smith, Elderand Co.

ocean, corals colonize the shoreline, taking the form of fringing reefs. As the volcano cools and subsides, the reefs grow upwards and outwards, away from the volcanic island, keeping pace with the local sea-level rise caused by subsidence. A shallow-water lagoon forms between the island and the living reef, comprising an offshore, perimeter barrier reef. In the final stage of subsidence, the island itself disappears below sea level to leave a ring of coral reef that marks the location of the sunken volcano; thus are atolls born.

Seldom more than a meter or two above sea level, all atolls and related sand-cay and gravel-motu islands are at the continuing mercy of the wind, waves, tides, and weather events that built them. They are dynamic features of the seascape; over timescales of decades to centuries they erode here, grow there, and sometimes disappear beneath the waves forever. A coral atoll is not so much a "thing" as a process, and they are obviously not good places on which to develop major human population centers.

Because they are located so close to sea level, it is commonly assumed atolls or coral sand/gravel islands (cays or motu) are vulnerable to rising sea level. But investigations into the processes that govern the formation, evolution, and stability of cays and motu indicate they are very resilient to sea-level changes, provided human activities do not disrupt the natural processes, such as by constructing sea walls (Perry *et al.*, 2011). Formation of cays and motu requires sufficient sediment supply and sufficient wave energy acting on the reef surface to transport and deposit sediment. Perhaps counterintuitively, overwashing of the islands by storm waves, storm surges, perigean tides, and tsunami is an important mechanism for increasing the elevation of the island by depositing new layers of sediment (Baines and McLean, 1976; Kench and Brander, 2006; Woodroffe, 2008; Etienne and Terry, 2012). When sea level rises, corals grow up to the higher sea level, normally easily keeping pace even at high rates of sea-level rise. When sea-level rise stops, the coral can grow only sideways.

Hence atolls are not a fixed "dipstick" with which to measure sea-level rise, as they are often treated: rather, a living coral reef forms part of a greater dynamic natural system. As Webb and Knetch (2010) write, "Typically, these [alarmist] studies treat islands as static landforms," but "such approaches have not incorporated a full appreciation of the contemporary morphodynamics of landforms nor considered the style and magnitude of changes that may be expected in the future. Reef islands are dynamic landforms that are able to reorganize their sediment reservoir in response to changing boundary conditions (wind, waves and sea-level)." Coral growth, erosion, transport, and deposition of sediment and the prevailing oceanography and meteorology must be taken into account. The very fact that we have so many coral islands in the world, despite a rise in sea level of more than 100 m since the last ice age, shows coral islands are resilient—they don't drown easily.

In essence, there appears to be an accommodation space, centered on mean sea level, that provides both the sediment and the energy needed to initiate and sustain coral cays and motu. Provided sea-level changes are slower than the rate at which the system can adjust the accommodation space, cays and motu are sustained. Rates of sea-level change for the foreseeable future are not high enough to threaten islands that are free to adjust in this way.

Connell (2003) found no evidence for the oft-repeated island doomsday claims about Tuvalu. Yamano *et al.* (2007) assessed 108 years of data for Fongafale Islet, Tuvalu, and found the problems attributed to sea-level rise in fact were due to population pressures resulting in the occupation of swamp land subject to periodic flooding throughout the historical record, thus demonstrating the great importance of real-world data—as opposed to climate model simulations—when it comes to considering the current and future status of Earth's many low-lying islands. As Yamano *et al.* (2007) state, "examinations of global environmental issues should focus on characteristics specific to the region of interest. These characteristics should be specified using historical reconstruction to understand and address the vulnerability of an area to global environmental changes."

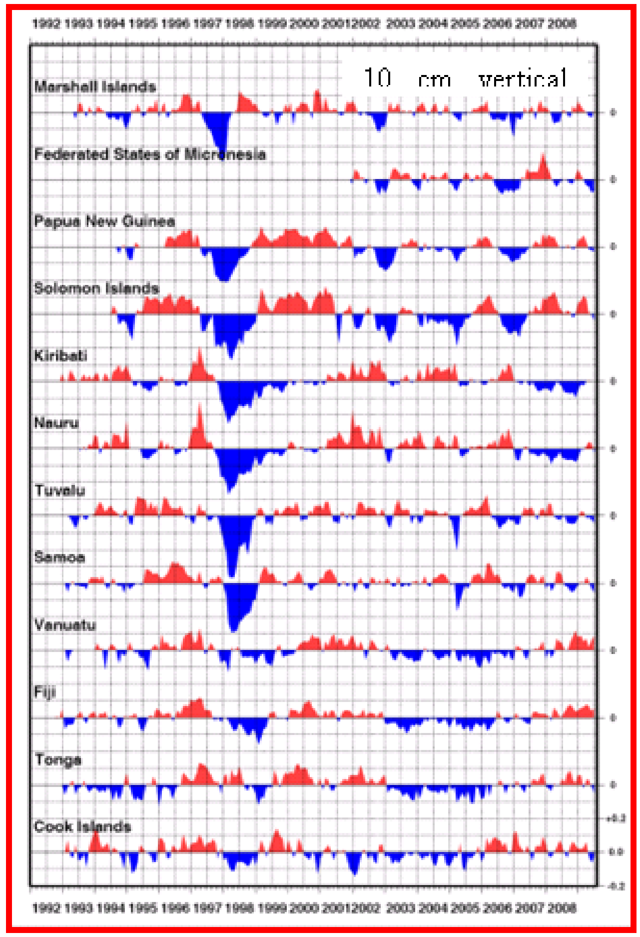
Webb and Kench (2010) found during the last part of the twentieth century 23 of the 27 Pacific atolls they studied remained unchanged or increased in area. They conclude, "The results show that island area has remained largely stable or increased over the time frame of analysis. Forty-three percent of islands increased in area by more than 3% with the largest increases of 30% on Betio (Tarawa atoll) and 28.3% on Funamanu (Funafuti atoll)." Over time, the island shapes changed in response to variations in dominant wave direction, and some islands migrated over their adjacent reef surfaces. A sensible management approach to this dynamic problem would be to design infrastructure so it can migrate with the evolving island, rather than attempt to maintain the island "frozen" in some arbitrary historical configuration.

In addition to the positive feedback loop of increased sediment supply demonstrated by Webb and Kench, the available evidence suggests the rate of long-term sea-level rise for most Pacific coral islands is less than the current global average rate of rise (see Figure 6.2.1.6.2). These records begin in 1993, when the Australian government set up a new series of accurate tide gauges to measure sea-level change on 14 tropical Pacific islands. At 19 years' duration, even the longest of the records is too short to provide accurate long-term trend signals that might be associated with global warming. As the authors point out, "Caution must be exercised in interpreting the short-term trends—they will almost certainly change over the coming years as the dataset increases in length."

No data exist to demonstrate an increasing, unusual, or unnatural rate of sea-level change for Pacific atolls, let alone any direct influence from increasing atmospheric carbon dioxide. As Meyssignac *et al.* (2012) conclude, "Results suggest that in the tropical Pacific, sea level trend fluctuations are dominated by the internal variability of the ocean-atmosphere coupled system. While our analysis cannot rule out any influence of anthropogenic forcing, it concludes that the latter effect in that particular region is still hardly detectable."

Conclusion

The dynamic nature of an atoll is exacerbated, and its integrity jeopardized, when it is subjected to the environmental pressures created by a growing human population. Sand mining, construction project loading, and rapid groundwater withdrawal all cause local lowering of the ground surface, thereby encouraging marine incursion quite irrespective of any sea-level change. It is these processes in combination with episodic natural hazards such as tides and storms, not global sea-level change, that provide the alarming video footage of marine flooding on Pacific Islands that from time to time appears on our television news.



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Earlier Research

Other recent papers on the effects of sea-level change on atolls or coral reefs are summarized below.

- Kench *et al.* (2005) proposed a new model for reef-island formation based on work conducted at the Maldives in the Indian Ocean. The model indicates island formation starts below sea level with the accumulation of sand and gravel bars. Once these catch up with sea level and emerge, the calcareous sediment is stabilized by vegetation and lithification (beach rock formation). Subsequently the growth of the island is determined by the supply of sediment through overwashing processes.
- McCoy *et al.* (2010) examined the Mamanuca Islands, Fiji, and found that although the islands were younger than the Maldives, the same model was valid. They conclude "contemporary development of the reef islands in the Mamanuca's and their links to sediment production on the reef flat suggests that they may be able to adjust their morphology to future environmental conditions."
- In a study of Raine Island (11°35'28"S, 144°02'17"E), outer Great Barrier Reef (Australia), Dawson and Smithers (2010) employed historic survey maps, topographic survey datasets of earlier researchers, and modern digital elevation data to reconstruct a 40-year (1967–2007) shoreline history of the island. Their analyses demonstrated Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007, and overall Raine Island underwent a net accretion of 68,400 ± 6,700 m^3 during that time. Dawson and Smithers conclude "future management strategies of Raine Island and other islands of the Great Barrier Reef should recognize that perceptions of reef island erosion can arise from large short-term seasonal and storm-derived sediment redistribution from one part of the island to another or to a temporary storage on the adjacent reef flat" but these phenomena do not necessarily lead to "a net permanent loss from the island sediment budget."
- Rankey (2011) based his integrated study of 17 islands on the Maiana and Aranuka atolls of Kiribati's Gilbert Island chain on integrated field observations, differential global positioning system data, historical aerial photographs, and ultrahigh-resolution remote sensing images. Examining the nature, spatial patterns, and rates of change of the shorelines of the islands he studied, Rankey found short-term (four-year) rates of shoreline change can indeed be dramatic, with significant intrusion of seawater over shallowly sloping shores. Over longer (40-year) periods the rates of change are much smaller and result in both slightly larger (growing) and slightly smaller (shrinking) islands. Rankey concludes "the atoll islands are not washing away" and counsels "solutions must consider the natural complexity of these [island] systems, rather than advocate overly

simplistic notions of the causes of, and the solutions to, coastal change."

- Ford (2012) reported on the shoreline status of Majuro Atoll, the capital and most populated atoll in the Republic of the Marshall Islands. He used a combination of aerial photos and satellite imagery to analyze shoreline change of the island over the past three-and-a-half decades, a period characterized by rapidly increasing population, coastal development, and a rising sea level on the order of 3 mm/year. Although the rural lagoon shore of Majuro Atoll has been predominantly eroding, Ford found, the ocean-facing shore has been largely accreting, and at a much faster rate. Within the urban area of Majuro he finds shoreline change "has been largely driven by widespread reclamation for a mix of residential, commercial and industrial activities." Thus, "despite a rising sea level … the landmass of Majuro has persisted and, largely because of reclamation, increased in size." Ford notes demands are placed on the limited land available as an atoll population increases, but for Majuro Atoll "it is likely that land reclamation will continue to satisfy this demand." He adds, "the notion that sea level rise is a singular driver of shoreline change along atolls is spurious," and "adopting such a notion is an impediment to the sustainable management of coastal resources within urban atolls."

- Dunne *et al.* (2012) studied rising sea levels around the shorelines of the Chagos Archipelago (which includes the Diego Garcia Atoll), Indian Ocean. Sheppard and Spalding (2003) had reported a tide gauge situated on Diego Garcia indicated a local sea-level rise of 5.44 mm/year for 1988–1999. Just three years later, another analysis of the same gauge for the slightly longer period 1988–2000 had reported a lesser rate of 4.35 mm/year (Ragoonaden, 2006). In Dunne *et al.*'s view both of these analyses "were based only on short tide-gauge datasets, involved inappropriate statistical methods, and as a result have given an erroneous impression of the magnitude and significance of sea-level rise in this area."

Dunne *et al.* used tide gauge and satellite altimeter records and ocean models and found "no evidence of any statistically significant sea-level rise either from the Diego Garcia tide gauge (1988–2000 and 2003–2011) or in the satellite altimetry record (1993–2011)." In addition, they note the lack of evidence for subsidence in the islands, consistent with GPS observations that Diego Garcia uplifted by 0.63 ± 0.28 mm/year between 1996 and 2009. Dunne *et al.* conclude, "collectively these results suggest that this has been a relatively stable physical environment, and that these low-lying coral islands should continue to be able to support human habitation, as they have done for much of the last 200 years."

Conclusions

On October 17, 2009, members of the Maldives' Cabinet donned scuba gear and used hand signals to conduct business at an underwater meeting staged to highlight the purported threat of global warming to the very existence of their country's nearly 1,200 coral islands. While underwater, they signed a document calling on all nations to reduce carbon (sic) emissions in response to the carbon dioxide threat.

The papers summarized above make it clear that observational and field evidence from a wide geographic range of low-lying ocean islands directly contradicts this theoretical threat.

Studies such as those by Webb and Kench (2010) and Dawson and Smithers (2010) have enabled a much better understanding of the likely effects of sea-level rise, should it happen, on low-lying islands. These effects include an increasing accommodation space for new coral reef growth and (bioclastic) sediment; reinvigoration of carbonate production on reef flats where further vertical reef growth today is inhibited by a stable or falling sea level; and an increase in the efficiency of waves to transport and accrete new and stored sediment to an island depocentre. The views of the Maldives Cabinet and its supporters notwithstanding, a rise in sea level on coral shorelines will most likely lead to an expansion of reef area and associated sediment banks. As Webb and Kench concluded, in contradiction of "widespread perceptions that all reef islands are eroding in response to recent sea level rise, … reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20–60 years."

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6.2.1.7. Other sea-level studies

We summarize in this section three recent sea-level studies that are not easily categorized.

- Woppelmann *et al.* (2008) examined "the issue of a possible tide gauge datum discontinuity for Brest … caused by the bombing of the city in August 1944," using historical leveling information and a comparison of sea-level data between adjacent stations. The Brest tide gauge was found to be "'stable' over the 1889–1996 period" because of the development of "an accurate datum connection between recently rediscovered 18th century sea level data (back to 1711) and those of the present day." An "interesting by-product" of their analysis was the close match that emerged between the Brest record and two long tide records in the U.K. at Liverpool and Newlyn. The three records show a roughly coincident increase in the rate of relative sea-level rise around the end of the nineteenth century, after which all three datasets define similar linear increases with time through to 2007.

If one splits the period of linear sea-level rise determined for Brest into two equal 57-year parts centered on the middle of the twentieth century—1893 to 1950 and 1950 to 2007—the two parts can be compared with an atmospheric CO_2 concentration that rose about 3.8 times faster over the second period than it did over the first. Since mean sea level rose at a constant rate over the entire 114 years, it is unlikely the historical increase in atmospheric CO_2 controlled the steady sea-level rise.

- Langley *et al.* (2009) studied the effect of rising sea level on coastal wetlands in the eastern United States with respect to plant growth and CO_2 concentration. In the microtidal Kirkpatrick Marsh of Chesapeake Bay, each of several 200m^2 plots was outfitted with a surface elevation table (SET) to measure soil elevation change. Langley *et al.* then exposed half the plots to an extra 340 ppm of CO_2 for two years, while "data from a greenhouse mesocosm experiment (Cherry *et al.*, 2009) were used to examine how elevated CO_2 might affect elevation response under simulated sea level rise scenarios."

The researchers found the plots with extra CO_2 increased fine root productivity by an average of 36 percent over the two-year study, and aboveground biomass production was increased by as much as 30 percent. These results were consistent with a 20-year record of elevated CO_2 treatment in a previous study on the same marsh by Erickson *et al.* (2007). The elevated CO_2 also caused an increase in root zone thickness of 4.9 mm/year compared with only 0.7 mm/year in the ambient CO_2 treatment, resulting in "a slight loss of elevation in ambient CO_2 (-0.9 mm/year) compared with an elevation gain (3.0 mm/year) in the elevated CO_2 treatment." Furthermore, Cherry *et al.* (2009) have determined from another greenhouse mesocosm experiment that "the CO_2 effect was enhanced under salinity and flooding conditions likely to accompany future sea level rise."

Langley *et al.* conclude, "by stimulating biogenic contributions to marsh elevation, increases in the greenhouse gas, CO_2, may paradoxically aid some coastal wetlands in counterbalancing rising seas." They note this finding bears "particular importance given the threat of accelerating SLR to coastal wetlands worldwide," such as the recent Environmental Protection Agency report of Reed *et al.* (2008), which suggested "a 2-mm increase in the rate of SLR will threaten or eliminate a large portion of mid-Atlantic marshes." Langley *et al.*'s research suggests the growth-promoting effect of atmospheric CO_2 enrichment will more than compensate for its hypothetical sea-level-raising effect.

- Albrecht *et al.* (2011) developed an index time series for changes in regional mean sea-level (RMSL) changes in the German Bight, North Sea. They employed two approaches—one that uses arithmetic means based on all available data for each time step, and another that uses empirical orthogonal functions. For comparison of their results with global mean sea-level data they used the 15 tide gauge dataset for 1843–2008 described and provided by Wahl *et al.* (2010, 2011).

Albrecht *et al.* report both methods produce similar results for the time period 1924–2008. Regional mean sea level increased at rates between 1.64 and 1.74 mm/year with a 90% confidence range of 0.28 mm/year in each case. Regarding possible acceleration in RMSL rise within the past few decades, they note in terms of 20-year trends, the most recent rates are "relatively high … but not unusual and ... similar rates could also be identified earlier in the record." Albrecht *et al.* reaffirm in the conclusion of their paper that "present rates of RMSL rise in the German Bight are relatively high, but are not unusual in the context of historical changes." Similar conclusions regarding recent acceleration were drawn by Haigh *et al.* (2009) for the North Sea region of the English Channel.

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6.2.1.8. Isostasy, GRACE

6.2.1.8.1 Isostasy

The reconstructed post-glacial sea-level curve of Figure 6.2.1.8.1.1 attempts to portray the true eustatic sea-level history of the past 20,000 years. To a first approximation, it is a history of the increasing volume of water in the world ocean caused by glacial melting and the steric expansion of a warming ocean. However, the measurements that underpin curves like this are made with respect to particular local relative sea levels at specific coastal locations and are affected by the movement up or down of the local geological substrate as well as by the notional global sea level.

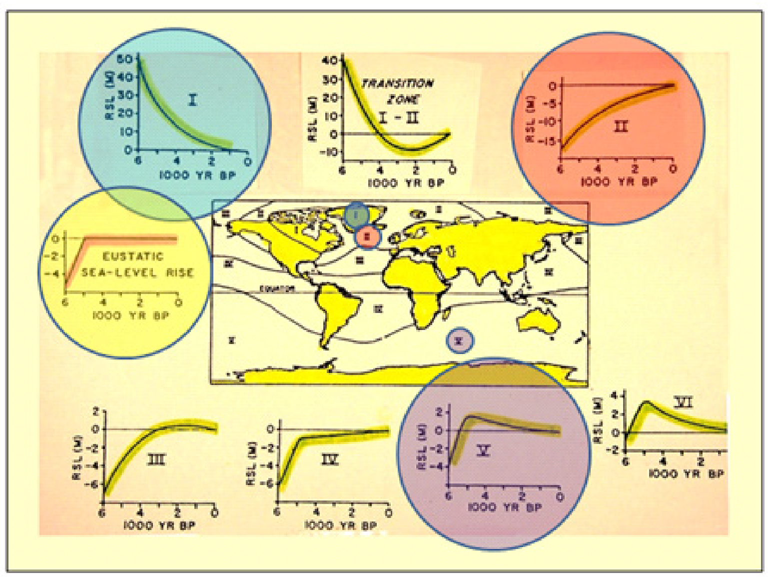

Figure 6.2.1.8.1.1. Local relative sea-level curves for the past 6,000 years, modeled to include hydro-isostatic effects combined with an idealized eustatic curve. Adapted from Clark, J.A. and Lingle, C.S. 1979. Predicted relative sea-level changes (18,000 Years B.P. to present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research* **11**: 279–298.

As the ice melted after the last glaciation, the increasing volume of the ocean caused two important changes to occur in the surface loading of Earth. First, the removal of an ice cap causes the formerly depressed (by loading) crust beneath to rebound upward by glacio-isostasy. Over 10,000 years during the Holocene, this rebound attained a magnitude of more than 100 meters at locations beneath the center of the former Scandinavian icecap, which are therefore characterized by falling post-glacial sea levels.

Second, an increasing ocean volume causes sea level to rise and the shoreline to transgress across the edges of the continental platforms, turning former glacial coastal plains into today's shallowly submergent continental shelf. The extra ocean water above the flooded continental shelf has the form of a coastline-parallel, landward-tapering prism, which provides a new crustal load that subsequently causes gentle hydro-isostatic uplift in the vicinity of the shoreline and hydro-isostatic sinking offshore, in both cases with a magnitude up to a few meters.

Overall, the effect is one of a seaward tilting of the crust beneath the continental shelf, with the rotational axis of tilting located near the sea-level high-stand shoreline (Chappell *et al.*, 1983; Tamisiea and Mitrovica, 2011).

In a classic 1979 paper, Clark and Lingle provided a modeled analysis of the way in which these isostatic effects combine with an assumed eustatic sea-level curve (see Figure 6.2.1.8.1.1, yellow circle) to produce a variety of local sea-level responses over the past 6,000 years that can be organized into recognizable geographic zones.

In proximal locations beneath former icecaps such as Greenland (blue circle; Zone I), strong glacio-isostatic rebound produces a falling relative sea-level. In far-field locations such as Australia and New Zealand (purple circle; Zone V), a shoreline overshoot of 2–4 meters at the end of the eustatic rise is followed by gradual relative sea-level fall in response to gentle hydro-isostatic deformation. And in intermediate locations such as the margins of the North Atlantic Ocean (red circle; Zone II), situated on the periphery of ice-sheet loading influence, interaction of these and other factors results in a relative sea-level curve that rises asymptotically to the present shoreline.

Isostatic uplift at a rate of, say, 2 mm/y (20 cm/century) may not sound like much on human generational time scales, but if the change is negative (land sinking) it is enough to more than double the "best estimate" 18 cm/century rate of global sea-level rise over the twentieth century. Conversely, if the change is positive (land rising), it is enough to convert that same eustatic rise into a falling rate of 2 cm/century. Obviously, and as Clark and Lingle were among the first to model, over geological timescales of millennia even small rates of isostatic depression or rebound can have a significant effect on the physiography of the shoreline and its position relative to local sea level.

The effect of these isostatic effects is displayed in Figure 6.2.1.8.1.2, which is a plot of the present-day elevations of more than 4,000 worldwide radiocarbon-dated shorelines of post-glacial age. Predictably, the pattern displayed is one of increasing elevation of particular shorelines above or below sea level with increasing time elapsed (i.e., from left to right across the figure), the sign of any plotted point indicating whether the sampled site is in an area of uplift or sinking. Accordingly, sites situated around sea level at 10,000 y BP (early Holocene) now occupy a range of elevations between about -100 m and +150 m, which indicates subsidence and uplift rates of up to -10 mm/y and +15 mm/y, respectively.

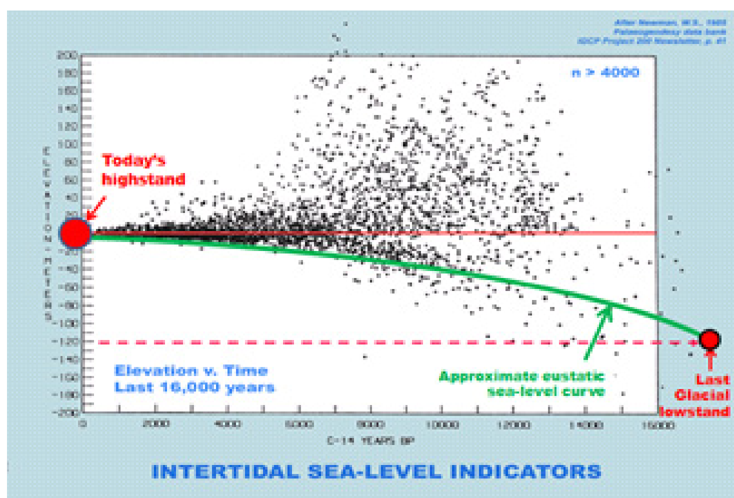

Figure 6.2.1.8.1.2. Worldwide plot of shoreline elevations with ages between 16,000 yBP and today. Adapted from Pirazzoli, P.A., Grant, D.R,. and Woodworth, P. 1989. Trends of relative sea-level change: past, present and future. *Quaternary International* **2**: 63–71. doi:10.1016/ 1040-6182(89)90022-0.

The large changes in ground level caused by glacio- and hydro-isostasy in the short period since the last glaciation serve as a warning regarding the naïve application of paleo-sea-level data from the previous interglacial, about 125,000 years ago. Sea-level indicators from the last interglacial also may be distorted by differing regional isostatic responses, but over about 100,000 rather than 15,000 years. It is thus inadvisable to use such data as predictors of future maximum sea levels during the present interglacial (Holocene and Recent).

The difficulty arises not only because of GIA variability in time and space, but also from longer-term uplift or depression in different tectonic provinces. Means of separating the sea-level and tectonic influences have been devised (Chappell, 1974), but they rely on assumptions of a fixed sea-level point in time. Even in locations thought to be unaffected by major crustal uplift or depression, geochronological ages suggest successive sea levels reached much the same elevation (van Vliet Lanoe *et al.*, 2000). Claims of a last interglacial sea level of between +6.6 and +9.4 m from a probabilistic analysis along allegedly stable coastline areas (Kopp *et al.*, 2009) contain circular arguments. In any event, what constitutes a stable region and how can such stability be shown? In addition, other crustal influences are usually ignored; Menard (1971) provided a map of oceanic crust, created since the last interglacial at mid-ocean ridge, that would have displaced sea level. The similar effects stemming from subduction zone changes have, to our knowledge, never been quantified.

Conclusions

IPCC commentary regarding sea level centers strongly on the calculation and manipulation of changes in the theoretical global average. But realistic management of sea level and other environmental issues cannot be undertaken at a global level, but rather must acknowledge the many and varied ways in which geological anisotropy imposes its signature at local and regional scales. Isostatic change—which is influenced by such factors as water and ice loading, rates of seafloor spreading and subduction, and even phase changes in the upper mantle—imposes an inescapable uncertainty on predictions of future climate-related sea-level change. Such change will be regionally variable and mostly of small magnitude over centennial time scales.

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6.2.1.8.2. GRACE

The conversion of satellite radar altimeter measurements into an accurate measure of the sea-surface level requires an accurate knowledge of both ocean mass and the shape of Earth, yet Earth's shape is constantly changing because of isostatic adjustments. Earth's shape is conventionally modeled as the geoid, which over the oceans is defined as the equipotential surface of Earth's gravity field that best fits, in a least squares sense, global mean sea level. One of the major difficulties of measuring sea-level changes from space is immediately apparent: The reference level is itself a function of the parameter being measured.

In 2002, twin orbiting satellites—the Gravity Recovery and Climate Experiment (GRACE)—were launched to provide better estimates of the ocean mass component of the sea-level budget. Although in principle the data provided by GRACE could lead to the accurate reconstruction of sea levels, the complex operational corrections that must be applied to spaceborne geophysical datasets mean "at best, the determination and attribution [in this way] of global-mean sea level change lies at the very edge of knowledge and technology" (Wunsch *et al.*, 2007).

Part of the processing of GRACE data is its correction in terms of an assumed model for glacial isostatic adjustment (GIA). Disappointingly, data from the GRACE satellites have not resulted in the establishment of the stable Terrestrial Reference Frame (TRF) needed for the development of an accurate GIA model. The lack of a stable TRF affects nearly all terrestrial satellite measurements, including those made with respect to sea level, ice mass, and others.

NASA's Jet Propulsion Laboratory (JPL) recently has acknowledged the importance of solving this problem by announcing a $100 million mission to launch a Geodetic Reference Antenna in Space (GRASP) satellite to improve the measurement of the TRF (geoid) used to calculate satellite sea-level measurements (NASA JPL, 2012). JPL acknowledges the current lack of an accurate model of Earth's reference frame has introduced spurious (and unknowable) errors into all satellite-borne sea-level, gravity, and polar ice cap volume measurements (Bar-Sever *et al.*, 2009).

A detailed analysis of processing and post-processing factors affecting GRACE estimates of ocean mass trends is provided by Quinn and Ponte (2010), who compare results from different GRACE data centers and explore a range of post-processing filtering and modeling parameters, including the effects of geocenter motion, postglacial isostatic rebound, and atmospheric pressure. Quinn and Ponte report the mean ocean mass trends they calculated "vary quite dramatically depending on which GRACE product is used, which adjustments are applied, and how the data are processed. For example, the isostatic rebound adjustment ranges from 1 to 2 mm/year, the geocenter adjustment may have biases on the order of 0.2 mm/year, and the atmospheric mass correction may have errors of up to 0.1 mm/year," with differences between GRACE data centers also being large, up to 1 mm/year.

Despite the inherent uncertainty of the results, GRACE satellite data have been used in several studies to estimate sea-level rise due to global warming. The particularly confounding factor in these studies is that continental edges and ocean basins respond to past and recent mass loss or additions by rising or sinking (Gehrels, 2010). Thus a falling sea level could reflect glacial isostatic rebound at the same time the actual worldwide trend was one of increasing ocean mass and consequent sea-level rise; and vice versa.

Leuliette and Miller (2009) assert "Global mean sea level change results from two major processes that alter the total volume of the ocean," and thus its mass. These processes are changes in total heat content and salinity, which produce density or steric changes; and the exchange of water between the oceans and other reservoirs, such as glaciers, icecaps, and land-based liquid water reservoirs. Although satellite radar altimeters have been providing data since the early 1990s, it is only since 2002 (GRACE) that global gravity estimates of mass variation have been available, and not until 2007 were accurate measurements made of global steric change (Argo ocean-profiling floats). It is probably for these reasons that prior attempts to close the global sea-level budget (Lombard *et al.*, 2007; Willis *et al.*, 2008) were unsuccessful.

Leuliette and Miller attempted a new analysis of the sea-level-rise budget for the period January 2004 to December 2007 using corrected Jason-1 and ENVISAT altimetric measurements, improved upper ocean steric data from the Argo array, and ocean mass variations calculated from GRACE gravity observations. The improved datasets closed the global sea-level-rise budget and indicated the sum of global steric sea level and ocean mass components had a trend of 1.5 ± 1.0 mm/year over the period of analysis. This result agrees with the measurements made by the Jason-1 (2.4 ± 1.1 mm/year) and ENVISAT (2.7 ± 1.5 mm/year) satellites within the 95% confidence interval.

Noting the last of these three results is 80 percent greater than the first, the question remains as to which result lies closest to the truth. Since Woppelmann *et al.* (2009) recently obtained a result of 1.58 ± 0.03 mm/year by analyzing GPS observations from a global network of 227 stations for the period 1997–2006, and given that both Church and White (2006) and Holgate (2007) obtained a result of 1.7 mm/year, it appears likely Leuliette and Miller (2009) have provided the most accurate result yet of any of the satellite altimeter studies.

Ivins *et al.* (2013) recalculated the contribution of Antarctic melt to sea-level rise using a claimed improved GIA correction. The GRACE data between January 2003 and January 2012, uncorrected for GIA, yield an ice mass rate of +2.9 ± 29 Gt/yr. The new GIA correction increases the solved-for ice mass imbalance of Antarctica to -57 ± 34 Gt/yr. The revised GIA correction is smaller than past GRACE estimates by about 50 to 90 Gt/yr, leading to a new upper bound to sea-level rise from Antarctic melt over the averaged years about 0.16 ± 0.09 mm/yr.

Baur *et al.* (2013) used GRACE data to assess continental mass variations on a global scale, including both land-ice and land-water contributions, for 19 continental areas that exhibited significant signals. This was accomplished for the nine-year period 2002–2011 using the GIA model of Paulson *et al*. (2007) to remove the effects of isostatic adjustment. In contrast to previous authors, Baur *et al.* stress "present-day continental mass variation as observed by space gravimetry reveals secular mass decline and accumulation," and "whereas the former contributes to sea-level rise, the latter results in sea-level fall." Reliable overall estimates of sea-level change must consider mass accumulation, rather than solely mass loss. Baur *et al.* report the mean mass gain and mass loss in their 19 primary areas was -0.7 ± 0.4 mm/year of sea-level fall and +1.8 ± 0.6 mm/year of sea-level rise, for a net effect of +1.1 ± 0.6 mm/year. To obtain a figure for total sea-level change, a steric component of +0.5 ± 0.5 mm/year (after Leuliette and Willis; 2011) was added, yielding a final uncorrected result of +1.6 ± 0.8 mm/year or a geocenter-corrected result of +1.7 ± 0.8) mm/year. These results are telling because the inferred rates of rise correspond almost exactly with the best- available independent measurements made with tide gauges (e.g., Church and White, 2006; Holgate, 2007).

Conclusions

Tide gauge reconstructions (Church and White, 2006) have found the rate of sea-level rise over the past century has been only 1.7 ± 0.5 mm/year. It seems strange to question this result using a GRACE-derived assessment with its many and potentially large errors and biases. Among other concerns, "non-ocean signals, such as in the Indian Ocean due to the 2004 Sumatran-Andean earthquake, and near Greenland and West Antarctica due to land signal leakage, can also corrupt the ocean trend estimates" (Quinn and Ponte, 2010).

Despite these problems, the latest GRACE estimates of Baur *et al.* (2012) correspond closely with their counterpart tide gauge estimates. Nonetheless, the GRACE satellites must develop a much longer history of satisfactory data acquisition before they can be considered a reliable means of providing accurate assessments of ocean mass and sea-level change. As Ramillien *et al.* (2006) have noted, "the GRACE data time series is still very short," so any results obtained from it "must be considered as preliminary since we cannot exclude that apparent trends [derived from it] only reflect inter-annual fluctuations."

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6.2.1.9. Computer modeling

Graphs projecting future sea level can be constructed in three ways: empirical, semi-empirical, and deterministic modeling. Papers using these techniques are referred to in many other places in this chapter; here we discuss the modeling techniques themselves.

6.2.1.9.1 Empirical models

An empirical model is constructed by plotting a series of mean sea-level measurements against time and then summarizing any trend present by fitting a statistical model, usually the best-fit straight line, to the ensemble of points (e.g., Figure 6.2.1.3.3 above). Extrapolation of the assumed relationship can be used to project future sea-level positions. These techniques fit a statistical relationship to existing data in order to provide some basis for extrapolation beyond the period of the dataset; importantly, this method provides rigorous estimates of the uncertainty of the projections made and therefore also provides measures of their goodness of fit.

In general, extrapolation of an empirical model cannot extend very far beyond the limits of the original data (say 10 percent) before the confidence limits diverge widely. Therefore, empirical models cannot usefully predict sea level very far into the future. Nonetheless, a good-quality 100-year-long tide gauge record should provide about a 20-year forward prediction within reasonable confidence limits. This should be sufficient to manage coastal development with a short design life and also to provide a good basis on which to develop adaptive and mitigation strategies.

6.2.1.9.2 Deterministic models

At the other extreme from empirical modeling in terms of computational complexity are deterministic computer programs. Based on the fundamental laws of physics, deterministic models can be used to make calculations of the likely position of future sea level based on theoretical grounds. The procedure involves initially developing scenarios of future economic activity and hence potential emissions of greenhouse gases. These scenarios are used to estimate the changes in radiative forcing and hence changes in global temperature. These data are then used in turn to estimate the response of the oceans and cryosphere in terms of ice melt, thermosteric expansion, and sea-level change.

Such modeling is based on the assumptions that all relevant factors are known and taken into account, that adequate theoretical understanding exists and can be expressed mathematically, and that the scenarios considered capture the actual trajectory of future events. These assumptions are not necessarily true.

The general circulation model (GCM) calculations of IPCC research groups are of the deterministic type (see Figure 6.2.1.9.1), and their outcomes are referred to as *projections* because, unlike empirical predictions, they do not have statistically meaningful confidence limits.

The projected changing global sea level generated by ocean warming and ice melting comprises the kernel of the IPCC's computer models

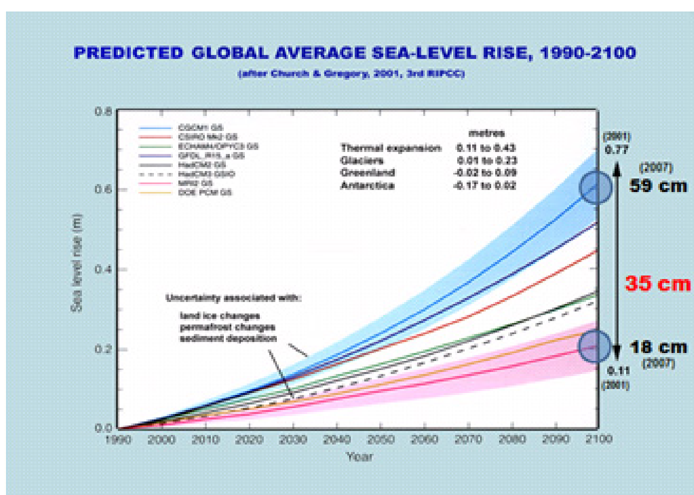

Figure 6.2.1.9.1. IPCC projections of sea-level rise between 1990 and 2100. Adapted from Intergovernmental Panel on Climate Change. 2001. *Climate Change 2001. 3rd Assessment Report of the Intergovernmental Panel on Climate Change.*

of the climate system. Ocean expansion can be directly related to warming of the surface mixed layer, but the melting of land ice is a more complex calculation that requires precise specification of surface temperatures. Ice does not necessarily melt if the surface temperature rises above 0° C; a small error can therefore make the difference between no melting and no sea-level change or actual melting and sea-level rise.

One difficulty with the deterministic approach is that it has proved difficult to identify the relative contributions to historical sea-level rise associated with the parameters modeled, so sea-level models have not predicted past sea levels well. It therefore remains unclear precisely how glacier and ice sheet behavior contribute to sea-level changes, although progress has been made since the first formal working group started their investigations in 1983 (Pfeffer, 2011). Thermosteric and halosteric sea-level changes also are not well constrained (Johnson and Wijffels, 2011). Since the Argo ocean-temperature profiling float array became fully operational in November 2007, some progress has been made on balancing the sea-level budget for the past decade (Leuliette and Willis, 2011), but it is not yet possible to extend the relationships back into the past with any degree of confidence (Wunsch *et al.,*2007).

The range of possible future sea-level changes projected by the IPCC and its predecessors has decreased progressively since the earliest reports produced for the UNEP (Hoffman *et al.,*1983). Due to the wide range of early projections and uncertainty about their validity, a future sea-level rise of 1 meter was commonly assumed for coastal impact assessments (SCOR Working Group 89, 1991), and that projection was included in the IPCC's *Second Assessment Report* in 1995. Considering the projections then currently used for coastal management, in its 2001 *Third Assessment Report* the IPCC provided a range of computer-generated projections for sea-level rise by 2100 of between 11 cm and 77 cm (Figure 6.2.1.9.1). They also estimated the current rate of sea-level rise of +1.8 mm/y was made up of contributions of 0.4 mm/y from thermal ocean expansion, 0.7 mm/y from ice melt, and 0.7 from dynamic oceanographic causes.

In the 2007 *Fourth Assessment Report* and using similar modeling, the IPCC adjusted the projected rise of sea level in 2100 to a range of 18–59 cm. The bottom end of this range corresponds with the 18 cm rise in sea level that results from extrapolating out to 2100 the long-term tide gauge rate of rise of 1.8 mm/y.

Church *et al.* (2011) compared the projections tuned by tide gauge data against the satellite altimetry trends, and Church and White (2011) reconstructed tide gauge data, concluding sea level is rising at the upper end of the IPCC projections. In contrast, the long-term tide-gauge- based sea-level rise reported by Church and White (1.7±0.2 mm/y), which they note is consistent with many other studies, falls right at the bottom of the IPCC projections (1.8 mm/y).

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6.2.1.9.3 Semi-empirical models

Between empirical and deterministic models lie other modeling techniques of moderate complexity that are collectively termed semi-empirical models. These models derive a relationship between sea level and temperature and then combine that relationship with a projected temperature scenario to estimate future sea-level rise. To their proponents, semi-empirical models are attractive because they are claimed to be superior to empirical models in making projections far into the future. Some of the most frequently cited are those by Rahmstorf (2007a), Vermeer and Rahmstorf (2009), Grinstead *et al.* (2010), and Rahmstorf *et al.* (2012).

The published results from semi-empirical models produce the highest and most alarming estimates of rates of future sea-level change so far published (between 0.8 and 1.8 m by 2100), and they conflict with projections based upon empirical or deterministic modeling. Accordingly, they are controversial and have attracted substantial criticism in the peer-reviewed scientific literature (Holgate *et al.*; Schmith *et al.*, 2007; Rahmstorf, 2007b).

The first of the semi-empirical studies (Rahmstorf, 2007a) proposed sea-level rise is a lagged response to temperature rise due to the greenhouse effect heating the ocean; the contribution from melting ice is also said to be a delayed response. These assumptions are directly contradicted by our knowledge of the last post-glacial sea-level rise (PALSEA, 2010; Section 6.2.1.1). In addition, the iterative smoothing process used by Rahmstorf during analysis has the effect of truncating the declining rate of sea-level rise observed in recent decades and inflating the correlation between sea level and temperature. The modeling also depends on the accuracy of IPCC emission scenarios known to be inaccurate (Castles and Henderson, 2003).

Some of these criticisms were taken into account in a modified version of the model, which includes an additional term and uses less smoothing, published by Vermeer and Rahmstorf (2009) (see Figure 6.2.1.9.2). However, the new term in the model reduces the effect of the slower rate of sea-level rise observed this century and maximizes the faster rate of the 1990s. These observed changes correspond to well-recognized decadal variability that is neither taken into account nor replicated in the 2009 Vermeer and Rahmstorf study.

The most recent iteration of Rahmstorf's semi-empirical model was published by Rahmstorf *et al.* (2012). This version of the model utilized several sea-level reconstructions, although only three are reported in the paper: the initial Church and White (2006) reconstruction; the revised global sea-level reconstruction of Church and White (2011); and the Jevrejeva *et al.* (2009) reconstruction. The 2011 reconstruction led to lower future sea-level rise than the older datasets, leading Rahmstorf *et al.* (2012) to

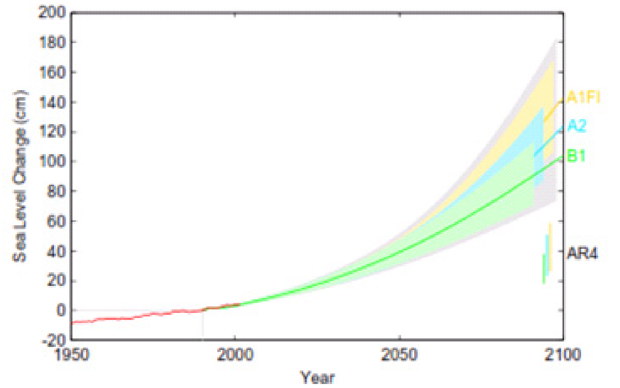

Figure 6.2.1.9.2. Projection of sea-level rise from 1990 to 2100, based on IPCC temperature projections for three emission scenarios (labeled on right). Adapted from Vermeer, M. and Rahmstorf, S. 2009. Global sea-level linked to global temperature, *Proceedings of the National Academy of Sciences* **106**: 21527–21532, Figure 6.

argue the 2009 projection (based on outdated data) is the most accurate.

The semi-empirical models suffer from a fatal flaw: They include no probability analysis. Yes, these studies project the possible magnitude of a future rise. But because hazard is defined in terms of both magnitude and frequency, by not expressing the probability they give only one half of the story. The important other half is that although a higher rate of rise than that observed historically is possible, it is also extremely unlikely.

Conclusions

The controversy surrounding the accuracy and policy usefulness of published semi-empirical models of sea-level change remains unresolved. Semi-empirical models have several known flaws, and given that both empirical and GCM modeling yield more modest projections of future sea level, semi-empirical model projections should be viewed with caution until their flaws are addressed (e.g., Church *et al.*, 2011).

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6.2.1.10. Mechanisms of sea-level change

Key issues in understanding eustatic (global) sea-level change include the degree to which glacial meltwater is causing an increase in ocean mass, the degree to which global warming may be causing thermosteric ocean expansion and hence sea-level rise, and the relative magnitude of direct human interferences with the fresh water budget such as dam building and ground water mining.

Research on most of these topics has been touched upon in many of the preceding sections of this chapter. We add below summaries of a small number of other papers conveniently handled under the three subheadings of 6.2.1.10.

6.2.1.10.1. Ice melt

Earlier Research

Papers addressing the issue of land-based ice melt as a cause of global sea-level rise include the following:

- Bindschadler (1998) analyzed the historical retreat of the West Antarctic Ice Sheet in terms of its grounding line (the boundary between the floating ice shelf and the "grounded" ice resting on bedrock) and ice front. He found the retreat of the ice sheet's grounding line has been faster than that of its ice front since the time of the last glacial maximum, which resulted in an expanding Ross Ice Shelf. Although the ice front now appears to be nearly stable, there are "indications that its grounding line was retreating at a rate that suggested complete dissolution of the WAIS in another 4,000 to 7,000 years." Such a retreat would result in a sustained sea-level rise of 8–13 cm per century. Bindschadler acknowledges even the smallest of these rates of rise would require a large negative mass balance for all of West Antarctica, a finding not supported by the data.
- Reeh (1999) summarized earlier work on the mass balance of the Greenland and Antarctic ice sheets. He concluded their future contribution to global sea level depends as much upon their past climatic and dynamic history as it does upon future climate. With respect to potential climate change, Reeh estimated a 1°C warming would create little net change in mean global sea level; Greenland's contribution would be a sea-level rise of only 0.30 to 0.77 mm/yr, while Antarctica's contribution, given that it is accreting mass, would be a sea-level fall of about 0.20 to 0.70 millimeters per year.
- Vaughn *et al.* (1999) used more than 1,800 measurements of the surface mass balance of Antarctica to produce an assessment of yearly ice accumulation over the continent. They found the "total net surface mass balance for the conterminous grounded ice sheet is 1,811 Gt yr-1 (149 kg m-2 yr-1) and for the entire ice sheet including ice shelves and embedded ice rises, 2,288 Gt yr-1 (166 kg m-2 yr-1)." These values are about 18 percent and 7 percent higher than current estimates derived about 15 years earlier. Some of the discrepancy may be explained by changes in net icefall over more recent years. The uncertainty leads Vaughn *et al.* to note, "we are still unable to determine even the sign of the contribution of the Antarctic Ice Sheet to recent sea-level change."
- Cuffey and Marshall (2000) reevaluated previous model estimates of the Greenland ice sheet's contribution to sea-level rise during the last interglacial using a recalibration of oxygen-isotope-derived temperatures from central Greenland ice cores. Their results suggest the Greenland ice sheet was much smaller during the last interglacial than previously thought, with melting of the ice sheet then contributing between 4 and 5.5 meters to sea-level rise. Hvidberg (2000) noted this finding suggests "high sea levels during the last interglacial should not be interpreted as evidence for extensive melting of the West Antarctic Ice Sheet, and so challenges the hypothesis that the West Antarctic is particularly sensitive to climate change."
- Wild and Ohmura (2000) studied the mass balance of Antarctica using two general circulation

models developed at the Max Planck Institute for Meteorology in Hamburg, Germany: the older ECHAM3 and a new and improved ECHAM4. Under a doubled atmospheric CO_2 scenario, the two models were in close agreement in their mass balance projections, with both predicting increases in ice sheet growth and therefore decreases in sea level.

- Van der Veen (2002) stressed the need to use probability density functions rather than single model outputs for policy-related sea-level research. He comments, "the validity of the parameterizations used by [various] glaciological modeling studies to estimate changes in surface accumulation and ablation under changing climate conditions has not been convincingly demonstrated." Uncertainties in model parameters are so great they yield a 95% confidence range of projected meltwater contributions from Greenland and Antarctica that encompass global sea-level lowering as well as rise by 2100 A.D., for all of IPCC's low, middle, and high warming scenarios. Van der Veen concluded confidence in current ice sheet mass balance models "is quite low," today's best models "currently reside on the lower rungs of the ladder of excellence," and "considerable improvements are needed before accurate assessments of future sea-level change can be made."
- Wadhams and Munk (2004) attempted "an independent estimate of eustatic sea-level rise based on the measured freshening of the global ocean, and with attention to the contribution from melting of sea ice (which affects freshening but not sea level)." Their analysis produced "a eustatic rise of only 0.6 mm/year," and when a steric contribution of 0.5 mm/year is added to the eustatic component, "a total of 1.1 mm/year, somewhat less than IPCC estimates," was the final result. Interestingly, the continental runoff "allowed" after subtracting the effect of sea-ice melt "is considerably lower than current estimates of sub-polar glacial retreat"; consonant with the mass balance models discussed above, this suggests a negative contribution to sea-level from polar ice sheets (Antarctica plus Greenland) or other non-glacial processes. Wadhams and Munk note, "we do not have good estimates of the mass balance of the Antarctic ice sheet, which could make a much larger positive or negative contribution."
- Oppenheimer and Alley (2005) discuss the degree to which warming can affect the rate of ice loss by altering the mass balance between precipitation rates on the one hand, and melting and ice discharge to the ocean through ice streams on the other, for both the West Antarctic and Greenland Ice Sheets. They conclude our knowledge is simply too incomplete to know whether these ice sheets have made a significant contribution to sea-level rise over the past few decades.
- Velicogna and Wahr (2006) used early measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellites to determine mass variations of the Antarctic ice sheet for the period 2002–2005. The two researchers conclude "the ice sheet mass decreased significantly, at a rate of 152 ± 80 km^3/yr of ice, equivalent to 0.4 ± 0.2 mm/yr of global sea-level rise." All of this mass loss came from the West Antarctic Ice Sheet; the East Antarctic Ice Sheet mass balance was 0 ± 56 km^3/year.

The Velicogna and Wahr conclusion should be viewed as provisional because of the many estimates and adjustments necessary during data reduction (see Section 6.2.1.8 for additional comments on the difficulty of using GRACE data). The adjustment for post-glacial rebound alone exceeded the signal being sought by nearly a factor of five. Moreover, the study covers less than a three-year period, and the result compares poorly with the findings of Zwally *et al.* (2005), who determined Antarctica's contribution to mean global sea level over a recent nine-year period was only 0.08 mm/yr.

- Ramillien *et al.* (2006) also used GRACE data to derive mass balance estimates for the East and West Antarctic ice sheets for the years 2002–2005. They calculated a loss of 107 ± 23 km^3/year for West Antarctica and a gain of 67 ± 28 km^3/year for East Antarctica, totaling a net ice loss for the entire continent of 40 km^3/year, a mean sea-level rise of 0.11 mm/year. This result is almost four times less than that calculated by Velicogna and Wahr. Ramillien *et al.* caution in their closing paragraph, "the GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations."
- Wingham *et al.* (2006) analyzed European remote sensing satellite altimeter data to determine the changes in volume of the Antarctic ice sheet from 1992 to 2003. They found "72% of the Antarctic ice sheet is gaining 27 ± 29 Gt per year, a sink of ocean mass sufficient to lower global sea levels by 0.08 mm per year." Wingham *et al.* contend this net extraction of water from the global ocean was driven by mass gains from accumulating snow, particularly on the Antarctic Peninsula and within East Antarctica.

- Remy and Frezzotti (2006) reviewed the results produced by estimating mass balance in three ways: measuring the difference between mass input and output; monitoring the changing geometry of Antarctica; and modeling both the dynamic and climatic evolution of the continent. They report "the current response of the Antarctica ice sheet is dominated by the background trend due to the retreat of the grounding line, leading to a sea-level rise of 0.4 mm/yr over the short-time scale [centuries]." They also note, "later, the precipitation increase will counterbalance this residual signal, leading to a thickening of the ice sheet and thus a decrease in sea level."
- Shepherd and Wingham (2007) reviewed 14 satellite-based estimates of sea-level contributions arising from wastage of the Antarctic and Greenland Ice Sheets since 1998. The earlier studies included standard mass budget analyses, altimetry measurements of ice-sheet volume changes, and measurements of the ice sheets' changing gravitational attraction. The results ranged from a sea-level-rise-equivalent of 1.0 mm/year to a sea-level-fall-equivalent of 0.15 mm/year. Shepard and Wingham concluded the current best estimate of the contribution of polar ice wastage from Greenland and Antarctica to global sea-level change was a rise of 0.35 mm/yr, i.e., a rate of 35 mm/century.

An important factor in many of these ice budget papers is the degree to which glacial wastage rates vary from year to year. For example, two of Greenland's largest outlet glaciers doubled their rates of mass loss in less than a year in 2004—causing the IPCC to claim the Greenland Ice Sheet was responding much more rapidly to global warming than expected—but by 2006 the mass loss had decreased to near the previous rates. Thus Shepherd and Wingham warn "special care must be taken in how mass-balance estimates are evaluated, particularly when extrapolating into the future, because short-term spikes could yield erroneous long-term trends."

- Krinner *et al.* (2007) applied the LMDZ4 atmospheric general circulation model of Hourdin *et al.* (2006) to simulate Antarctic climate for the periods 1981–2000 (to test the model's ability to adequately simulate recent conditions) and 2081–2100 (to assess the future mass balance of the Antarctic Ice Sheet and its impact on global sea level). They conclude the simulated Antarctic surface mass balance increases by 32 mm water equivalent per year, which corresponds to a sea-level decrease of 1.2 mm per year by the end of the twenty-first century. This would lead to a cumulated sea-level decrease of about 6 cm. They note the simulated temperature increase "leads to an increased moisture transport towards the interior of the continent because of the higher moisture holding capacity of warmer air," where the extra moisture falls as precipitation and causes the continent's ice sheet to grow.
- In a study of Alaskan and nearby Canadian glaciers, Berthier *et al.* (2010) pointed out earlier estimates of mass loss from Alaskan and nearby glaciers (Arendt *et al.*, 2002; Meier and Dyurgerov, 2002; Dyurgerov and Meier, 2005) relied on extrapolating site-specific measurements to the entire region. For example, Arendt *et al.* (2002) used laser altimetry to measure elevation changes on 67 glaciers, but those glaciers represented only 20 percent of the area of the ice field.

To overcome this and other deficiencies, Berthier *et al.* attempted to calculate ice elevation changes for nearly three-quarters of the ice-covered areas in Alaska by measuring elevation changes derived from sequential digital elevation models for the period 1962–2006. They found, "between 1962 and 2006, Alaskan glaciers lost 41.9 ± 8.6 km^3 of their volume over the measured period, thereby contributing 0.12 ± 0.02 mm/yr to sea-level rise." This estimate is 34 percent less than those of Arendt *et al.* (2002) and Meier and Dyurgerov (2002), an indication of the inherent errors in this type of research. Berthier *et al.* comment, "estimates of mass loss from glaciers and ice caps in other mountain regions could be subject to similar revisions."

- Nick *et al.* (2013) developed a glacier flow model incorporating the dynamic behavior of marine glacial termini affected by ocean conditions. This model was applied to four marine-terminating glaciers that account for 22 percent of the flow from the Greenland Icecap. Assuming 2.8° C of warming by 2100, they simulated the atmospheric and oceanic effects on ice discharge and projected a sea-level contribution of 19–30 mm by AD 2200 (0.01–0.06 mm/y per glacier after an initial rapid loss associated with over-deepenings in the glacier troughs). These estimates are considerably lower than those derived by Pfeffer *et al.* (2008) of 36–118 mm for the 22 percent of glacier flow (or 165–538 mm for all of Greenland) by AD 2100.

Conclusions

Considerable uncertainty attends our knowledge of the water balance of the world's oceans and the melting of on-land ice. These uncertainties must be resolved before we can confidently project effects such as sea-level change.

It appears there has been little recent change in global sea level due to wastage of the West Antarctic Ice Sheet, and such coastal wastage as might occur over the long term is likely to be countered, or more than countered, by greater inland snowfall. In such circumstances the sum of the response of the whole Antarctic Ice Sheet might well compensate for any long-term wastage of the Greenland Ice Sheet, should that happen.

Regarding the Northern Hemisphere, the Arctic regions have been cooling for the past half-century, and at a very significant rate, making it unlikely Greenland's frozen water will be released to the world's oceans anytime soon. This temperature trend is just the opposite—and strikingly so—of that claimed for the Northern Hemisphere and the world by the IPCC. Accompanying the cooling, the annual number of snowfall days over parts of Greenland has also increased strongly, so an enhanced accumulation of snow there may be compensating for the extra runoff coming from mountain glaciers that have been receding.

The balance of the evidence from both hemispheres indicates little net sea-level change is currently occurring as a result of accentuated ice melt. It remains entirely possible the global cryosphere is actually growing in mass.

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6.2.1.10.2. Thermosteric

Lombard *et al.* (2005) used the global ocean temperature data of Levitus *et al.* (2000) and Ishii *et al.* (2003) to investigate the thermosteric, or temperature-induced, sea-level change of the past 50 years. A net rise in sea level occurred over the full half-century period, but superimposed on that are marked decadal oscillations that represent ocean-atmosphere climatic perturbations such as the El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation. Lombard *et al.* recognized these as thermosteric trends over 10-year windows that showed large fluctuations in time, with positive values (in the range 1 to 1.5 mm/year for the decade centered on 1970) and negative values (-1 to -1.5 mm/year for the decade centered on 1980).

The record shows only an overall trend because it began at the bottom of a trough and ended at the top of a peak. In between these two points, there were both higher and lower values, so one cannot be sure what would be implied if earlier data were available or what will be implied as more data are acquired. Lombard *et al.* noted similar sea-level trends that occur in TOPEX/Poseidon altimetry over 1993–2003 are "mainly caused by thermal expansion" and thus probably not a permanent feature. They conclude, "we simply cannot extrapolate sea level into the past or the future using satellite altimetry alone."

If even the 50 years of global ocean temperature data we possess are insufficient to identify accurately the degree of global warming and related sea-level rise that has occurred over the past half-century, it will be many decades before satellite altimetry can identify a real climatic trend.

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6.2.1.10.3. Dam storage and groundwater depletion

Two human on-land development practices can have a material effect on sea level: the building of dams and reservoirs, which withhold water that would otherwise have flowed to the ocean; and the extraction of groundwater, which, after use, contributes water to the ocean that otherwise would have remained stored on the continent. The net freshwater run-off is thereby altered, with the first practice acting to lower sea level and the second practice helping to raise it.

Though they act in opposite directions and are small in the natural scheme of things, these effects are not entirely negligible (e.g., Sahagian *et al.*, 1994; Gornitz *et al.*, 1997; Konikow and Kendy, 2005, Huntington, 2008; Lettenmaier and Milly, 2009; Milly *et al.*, 2010). Konikow (2011) recently summarized the situation with respect to groundwater removal by compiling the first comprehensive aquifer-based estimate of changes in groundwater storage using direct volumetric accounting. Konikow then compared the groundwater depletion results he obtained with sea-level rise observations.

Konikow established groundwater depletion over the period 1900–2008 was about 4,500 km^3, equivalent to a global sea-level rise of 12.6 mm, or just over 6 percent of the total observed rise. Perhaps not surprisingly, the rate of groundwater depletion has increased markedly since about 1950, with maximum rates occurring during the most recent period (2000–2008), when extraction averaged ~145 km^3/year. The average rate of sea-level rise over the twentieth century was 1.8 ± 0.5 mm/year (Church *et al.*, 2011); Konikow's work suggests on average 0.12 mm/yr of this rise may have resulted from additional groundwater runoff.

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6.2.1.11. Policy: What is the problem?

The fear that human carbon dioxide emissions may cause dangerous sea-level rise beyond natural rates and levels has focused policy attention on cutting emissions. The preceding parts of Section 6.2 have demonstrated there is very little evidence to support the CO_2-sea level rise hypothesis. No evidence (as opposed to computer model speculation) shows the human component of atmospheric carbon dioxide levels is materially influencing sea level to behave outside its usual natural envelope of change.

Based on geological studies, it appears global sea-level rise has been taking place at a slowing rate over the past 10,000 years (cf., Figure 6.2.1.1.2). At specific locations, this rising trend interacts with tectonic factors, isostatic effects, and multidecadal rhythmicity to produce different patterns of local relative sea-level change that vary from place to place and region to region (Figure 6.2.1.8.1.1). It is also established by many studies that over the past 150 years eustatic sea level has been rising at an average rate of about 1.8 mm/y, which represents the slow continuation of a melting of the ice sheets that began about 17 ka. The IPCC estimates 1.1 mm of this rise can be accounted for by the combined effects of continuing ice melt (~0.4 mm/y) and steric ocean expansion (~0.7 mm/y), and that the residuum, if correctly estimated, probably relates to dynamic oceanographic and meteorological factors.

There is, therefore, no scientific basis for the oft-repeated suggestion that "global warming" will melt so much ice that sea levels will imminently rise by Al Gore's imagined 20 feet. In four successive *Assessment Reports* between 1990 and 2007, the IPCC has reduced its estimate of the maximum sea-level rise by the year 2100 from 367 to 124 to 77 to 59 cm, a reduction of the speculated rise of more than 80 percent. Moreover, IPCC 2007 assumed most of the projected increase arises from a slow (centuries) thermosteric expansion of the oceans, which produces a sea-level rise of only 20–60 cm per 1°C increase in globally averaged warming (Church *et al.,*2011). Furthermore, warming is currently not occurring at the projected rate. Should they continue to melt, glaciers and ice caps are expected to contribute another 12±4 cm by 2100 (Church *et al.,*2011). Ice sheet contributions are less certain because of large variations in estimates of ice volume losses. However, an upper estimate based on extrapolating a short record is 56 cm by 2100 (Pfeffer, 2011).

Conclusions

The problem is not global sea-level change, which, using a naïve forecasting approach, is projected to rise by only about 18 cm by 2100. Instead the problem is uncertainty. That uncertainty applies to future global temperature change, future ice accretion or melting, and future global sea-level change—and it is profound**.**

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Management and planning for the real hazard

Sea levels change naturally, constantly, and all over the world at different rates and in opposing directions. In addition, the effect of sea-level change is almost exclusively a matter of coastal management, a fact that has not been widely recognized. Outside of very shallow coastal waters, whether the sea level is higher or lower is of no practical concern for shipping activities or other human ocean uses such as erecting offshore petroleum production platforms or laying deep-sea communications cables. Thus at the heart of the issue of sea-level policy lies the need for an understanding of coastal processes.

The position and stability of a shoreline depends upon a number of factors. One of these is local mean sea level. But several other important natural processes also operate within and upon the coastal environment, including geomorphology, sediment supply, and mean and extreme conditions of wind, weather, and near-shore oceanography. The shoreline also is affected by human development.

In most countries, coastal management is traditionally undertaken by a local or regional council of some type, operating within a legal framework provided by either a state or national government (French, 1997). The local agencies deal with such matters as beach erosion and harbor dredging, and they establish and enforce land-use and building regulations addressing what types of structures may be built where. In implementing coastal policy, lawmakers and their staff traditionally have been guided by experienced, legally accountable, professional coastal engineers and scientists. Until recently, therefore, cost-benefit analysis of coastal policy was generally alive and well at the local and regional level of governance and administration.

Which is, of course, not to say historic coastal management has been perfect. One particular defect has been inadequate control over dense coastal development that later proves to be inadequately sited to withstand the effects of rare and episodic super storms. The "hurricane" Sandy storm in northeastern USA provides a case in point. The strong wave surges and winds that imposed such destruction on the northeast's poorly located coastal communities were caused by the merging of two separate storm systems. Though this was a rare event, in a general sense it was entirely predictable, and the occurrence of Sandy should act as a wake-up call for the need for more cautious attitudes to coastal development.

Since 1988, traditional, locally oriented coastal management has increasingly come to be replaced by planning based on global environmental principles, as the IPCC commenced advising governments about global sea-level change. The advent of IPCC's global warming advice usurped the traditional policy process through which governments drew their advice about sea-level change from statutory authorities concerned with harbor and tidal management and from formal governmental scientific agencies. Because the IPCC is tasked to ponder global warming, after its formation the focus of governments shifted from seeing sea-level change as a beaches, ports, harbors, and navigational issue to seeing it as an environmental issue related to hypothetical global warming caused by human carbon dioxide emissions.

As part of this change, attention shifted away from basing public policy on the use of measured tide gauge records of sea level (see Figure 6.2.1.2.1) to basing it on the theoretical projections of computer models (such as Figures 6.2.1.9.1 and 6.2.1.9.2). By the turn of the twentieth century, governments around the world, and their advisory scientists, were basing their sea-level planning almost exclusively on the advice of the IPCC; i.e., on unvalidated computer model predictions tied not to accurate local sea-level measurements but to a theoretical geoid that floats in mathematical space.

Because IPCC sea-level predictions were and are for a global average sea level, we thus arrived at our present unsustainable position, which is one of governments fashioning policy and new laws predicated upon a notional statistic and in almost complete disregard of the local real measurements available from tide gauge networks. Many countries or states have passed measures that require their coastal authorities to base planning on IPCC's assumed 59 cm rise by 2100, or higher. For example, the Australian states of Victoria and New South Wales have set planning benchmark levels of 80 cm and 90 cm, respectively.

Abandoning traditional, empirical methods of dealing with coastal management issues and adopting (sometimes exaggerating) the IPCC's uncertain, model-based sea-level projections has introduced much additional and unrecognized uncertainty into policy planning. Uncertainty surrounds the global temperature projections that feed into sea-level modeling and affects the relationship between global temperature change and polar land ice melting rates. Moreover, we lack accurate knowledge of the glacial isostatic anomaly.

Conclusions

Based on this discussion and the other material presented in this chapter, three obvious policy guidelines present themselves for implementation.

Abandon "let's stop global sea-level rise" policies
No justification exists for continuing to base sea-level policy and coastal management regulation on the outcomes of deterministic or semi-empirical sea-level modeling. Such modeling remains highly speculative. Even if the rate of eustatic sea-level change was known accurately, the practice of using a notional global rate of sea-level change to manage specific coastal locations worldwide is irrational, and it should be abandoned.

Recognize the local or regional nature of coastal hazard
Most coastal hazard is intrinsically local in nature. Other than periodic tsunamis and exceptional storms, it is the regular and repetitive local processes of wind, waves, tides, and sediment supply that fashion the location and shape of the shorelines of the world.

Yes, local relative sea level is an important determinant, but in some localities it is rising and in others falling. Accordingly, there is no "one size fits all" sea-level curve or policy that can be applied. Coastal hazard can be managed effectively only in the context of regional and local knowledge and using data gathered by site-specific tide gauges and other relevant instrumentation.

Use planning controls that are flexible and adaptive
The shoreline is a dynamic geomorphic feature that quite naturally moves with time in response to changing environmental conditions. Many planning regulations already recognize this; for example, by applying minimum building setback distances or heights from the tide mark. In addition, engineering solutions (groynes, breakwaters, sea-defense walls) often are used to stabilize a shoreline. If they are effective and environmentally acceptable, such solutions should be encouraged.

Nevertheless, occasional damage will continue to be imposed from time to time by large storms or other unusual natural events, no matter how excellent the preexisting coastal engineering and planning controls may be. In these circumstances, the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur. It is the height of futility and a waste of scarce financial resources to attempt to "control" the size or frequency of large natural events by expecting that reductions in human carbon dioxide emissions will moderate climate "favorably," including expectations of a reduced rate of global sea-level rise.

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6.2.2. Ocean Heat

Earth's climate is not controlled solely by the atmosphere but also to a large degree by the heat stored in the ocean, which has a 3,300 times greater heat capacity than the atmosphere. With an average global circulation time of roughly 1,000 years, compared with one year for the atmosphere, changes in the release or uptake of ocean heat operate over the longer multidecadal, centennial, and millennial time scales associated with climate change, as opposed to weather variability.

The exchange of ocean heat via currents and wind-enhanced ocean-atmosphere interactions drives weather at all scales of both space and time. Particular, repetitive weather patterns occur over the ocean itself and exercise far-reaching influence on adjacent landmasses. For example, the wet, warm winds that blow from the ocean to the continental interior in the Pacific Northwest of USA (Chinook wind, in original usage) can raise winter temperature from -20°C to more than +10°C and melt 30 cm or more of snow in a single day. Monsoon systems are another case in point, where seasonal differential heating of a landmass and its nearby ocean cause a reversal of winds from offshore to onshore at the start of the monsoon, often causing torrential rainfall deep into the continental interior.

Despite its critical importance for climatic studies, we have a poor record of ocean heat observations, and it is only since the inception in 2004 of the Argo global network of more than 3,000 ocean profiling probes that we have an adequate estimate of ocean temperatures and heat budget. Though Argo data are in their infancy and subject to adjustment for errors, early indications are that the oceans are currently cooling (Loehle, 2009).

Shaviv (2008) explored some of the key issues relating to change in ocean heat as a driver of climate change, particularly in response to solar variations. He writes, "climatic variations synchronized with solar variations do exist, whether over the solar cycle or over longer time-scales," citing numerous references. Nonetheless, many scientists decline to accept the logical derivative of this fact: Solar variations are driving climate changes. They say measured or reconstructed variations in total solar irradiance (TSI) seem too small to be capable of producing observed climate change.

That concern can be addressed in two ways. The first is to observe that aspects of Earth-sun energy interrelations other than TSI are known to play a role, and perhaps a significant role, in climate change. These mechanisms, addressed in Chapter 3, include:

- Variations in the intensity of the Sun's magnetic fields on cycles that include the Schwabe (11 year), Hale (22 year), and Gleissberg (70–90-year) periodicities;

- The effect of the sun's plasma and electromagnetic fields on rates of Earth rotation, and therefore the length of day (LOD);

- The effect of the sun's gravitational field through the 18.6-year-long Lunar Nodal Cycle, which causes variations in atmospheric pressure, temperature, rainfall, sea level, and ocean temperature, especially at high latitudes;

- The known links between solar activity and monsoonal activity, or the phases of climate oscillations such as the Atlantic Multidecadal Oscillation, a 60-year-long cycle during which sea surface temperature varies ~0.2° C above and below the long-term average, with concomitant effects on Northern Hemisphere air temperature, rainfall and drought; and

- Magnetic fields associated with solar flares, which modulate galactic cosmic ray input into Earth's atmosphere and in turn may cause variations in the nucleation of low-level clouds at up to a few km high (Ney, 1959; Dickinson, 1975; Svensmark, 1998). This causes cooling, a 1 percent variation in low cloud cover producing a similar change in forcing (~4 W/m^2) as the estimated increase caused by human greenhouse gases. This possible mechanism is controversial and is being tested in current experiments devised at the European Organization for Nuclear Research (CERN). But irrespective of the results of these experimental tests and of the precise causal mechanism, Neff *et al.* (2001) have provided evidence from palaeoclimate records for a link between varying cosmic radiation and climate (see Figure 6.2.2.1). Using samples from a speleothem from a cave in Oman, Middle East, they found a close correlation between radio-carbon production rates (driven by incoming cosmic radiation, which is solar-modulated) and rainfall (as reflected in the geochemical signature of oxygen isotopes).

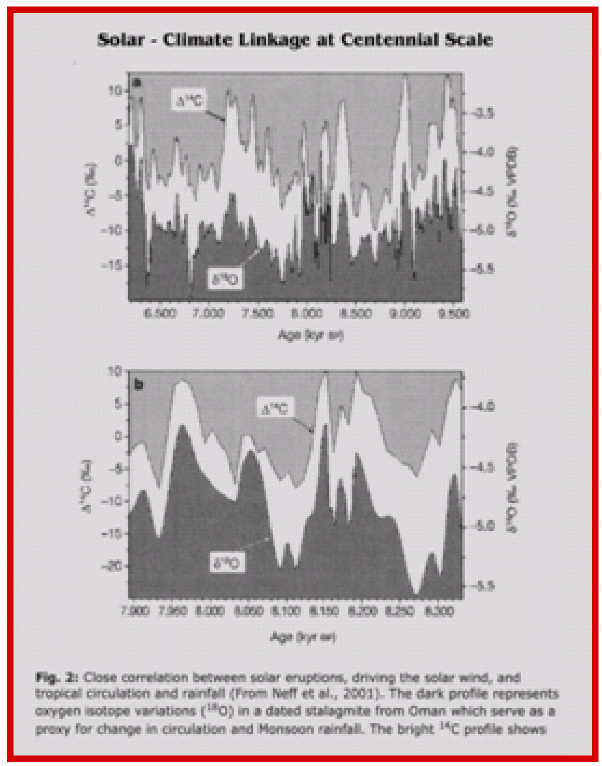

Figure 6.2.2.1. Correlation between proxies for incoming cosmic radiation (radiocarbon production) and rainfall (oxygen isotope signature) from an Oman spleothem. Adapted from Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A. 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* **411**: 290–293.

- The 1,500-year-long Bond Cycle is probably also of solar origin, and another climate rhythm of similar length, the Dansgaard-Oeschger (D-O) cycle, occurs especially in North Atlantic glacial sediments deposited about 90,000–15,000 years ago.

A second way of resolving the too-weak-TSI dilemma would be the discovery of an amplification mechanism of the weak solar radiation signal. Shaviv (2008) makes a good case for the existence of such an amplifier. Shaviv used the oceans as a calorimeter with which to measure the radiative forcing variations associated with the solar cycle. He studied “three independent records: the net heat flux into the oceans over 5 decades, the sea-level change rate based on tide gauge records over the 20th century, and the sea-surface temperature variations, each of which can be used independently to derive the oceanic heat flux.”

Shaviv discovered large variations in oceanic heat content associated with the 11-year solar cycle. In addition, the datasets “consistently show that the oceans absorb and emit an order of magnitude more heat than could be expected from just the variations in the total solar irradiance.” This clearly implies the existence of an amplification mechanism, although without pointing precisely to what that might be.

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6.2.2.1. Ocean Heat Measurement

Ocean heat content is determined by extrapolating vertical temperature and salinity profile data collected by a range of techniques at different sampling densities (Emery and Thomson, 2001). The specific heat of seawater is a complex function of temperature, salinity, and pressure (Fofonoff and Millard Jr., 1983), so all three parameters are required to estimate the heat content within a profile. Due to the high heat capacity of water (~4 $kJ.kg^{-1}.°C^{-1}$), small changes in temperature result in significant changes in specific heat depending on salinity and pressure (see Figure 6.2.2.1.1). Small errors in temperature measurement thus result in large errors in estimated heat content. This leads to special difficulties in the modern use of older data. Early data obtained by hydrocasts were manually error-checked by comparing the measured profiles with the “expected” or “known” trends, leading Emery and Thomson to comment, “As a matter of curiosity, it would be interesting to determine the number of deep hydrocast data that were unknowingly collected at hydrothermal venting sites and discarded because they were ‘erroneous.’”

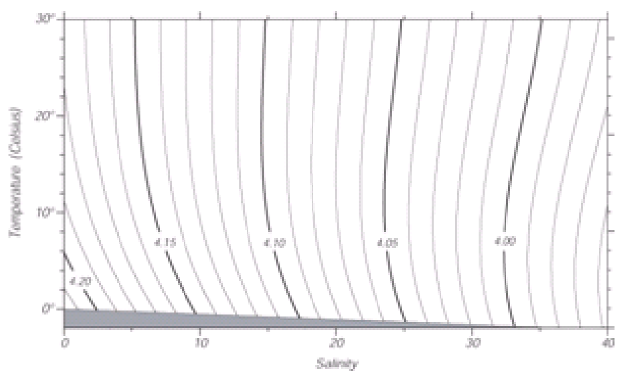

Figure 6.2.2.1.1. Specific heat of seawater in $J.g^{-1},°C^{-1}$ at atmospheric pressure for a typical range of ocean temperatures and salinities. Stuart, Robert H. (2008) *Introduction to Physical Oceanography*. Chapter 5, The Oceanic Heat Budget, Figure 5.1. oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book.pdf.

Deep ocean conditions were measured by hydrocasts using different sensor types lowered and then raised to the surface. Typically the collected data displayed hysteresis[3] due to the relatively slow response times of the sensors. Subsequently, profiles were obtained by expendable bathythermographs (XBTs), which measure only a descent profile, or profiling floats that measured descent and ascent profiles in different locations to correct for variable periods of drifting between ascent/descent.

Surface layer temperatures have been measured by buckets, inlet temperatures for engine cooling

[3] Data collected during the descent tended to be too warm, and during the ascent too cold. Averaging the two profiles was assumed to give a more reliable estimate of the true conditions.

systems, and thermistor strings suspended from surface buoys. Finally, the skin temperature of the ocean can be estimated from the infrared radiation emitted as observed by satellite or airborne sensors (Emery and Thomson, 2001). This wide range of measurement techniques makes direct comparisons of ocean heat between repeat surveys problematic.

In addition, the sample coverage of the oceans is relatively sparse, particularly before the Argo array of profiling floats achieved near global coverage in 2004. Hence, the measured heat contents are extrapolated over large volumes to estimate the global heat content. This has led some studies to conclude ocean heat can be determined only since 1993 (Lynman *et al.* 2010). Carson and Harrison (2008) demonstrated inferred warming of the ocean was largely a consequence of the data interpolation methodologies used, which tended to be biased toward the 30 percent of the ocean regions that warmed and ignored regions that had cooled.

Quite large variations among even recent studies are evident (Lynman *et al.*, 2010). Willis *et al.* (2009) compare results determined from different data sources over a three-year period (see Figure 6.2.2.1.2). All data taken together indicated cooling; XBT data and estimates from satellite altimetry indicated a slight cooling; and Argo data excluding known faulty floats indicated slight cooling. The faulty Argo floats strongly influenced the results. In addition, the Argo floats found lower ocean heat content than the other data sources. Since the proportion of data derived from Argo floats increased with time, Willis *et al.* suggest the combination of data sources also created a cooling bias.

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Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852.

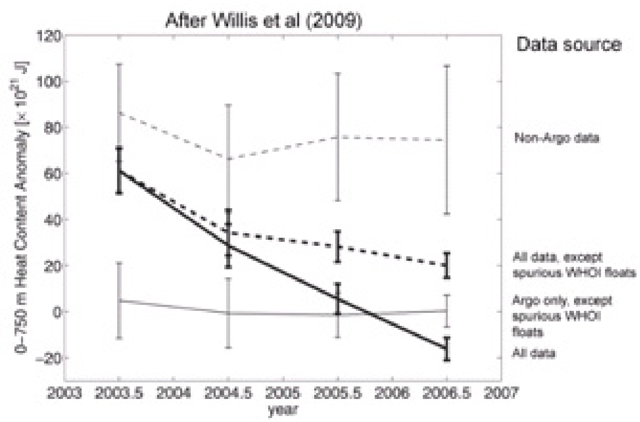

Figure 6.2.2.1.2. Comparison of global ocean heat content changes for the upper 750 m of using different combinations of data sources. Adapted from Willis, J.K., Lyman, J.M., Johnson, G.C., and Gilson, J. 2009. In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology* **26**: 846–852, Figure 4.

6.2.2.2. Ocean Heat Trends

Willis *et al.* (2009) point out "as the Earth warms due to the buildup of greenhouse gases in the atmosphere, the majority of the excess heat is expected to go toward warming the oceans (Levitus *et al.*, 2005; Hansen *et al.*, 2005)." In contradiction of this expectation, a significant cooling in the ocean heat content anomaly (OHCA) was reported between 2003 and 2005 by Lyman *et al.* (2006).

As discussed in the previous section, Willis *et al.* (2009) concluded the cooling reported by Lyman *et al.* (2006) was an artifact caused by XBT warm bias and Argo cold bias because of the changing proportion of data sources over time. They concluded "OHCA does not appear to exhibit significant warming or cooling between 2003 and 2006." Willis *et al.* also note the absence of a significant cooling signal in the adjusted OHCA results "brings estimates of upper-ocean thermosteric sea level variability into closer agreement with altimeter-derived measurements of global mean sea level rise."

Domingues *et al.* (2008) adjusted their estimates of ocean heat content to match sea-level changes as determined by Church and White (2006). The period of analysis, from 1950 to 2003, excludes the Argo data. They found an increase in ocean heat content, mostly between 1970 and 2003, with significant multidecadal oscillations that do not fit volcanic eruptions or ENSO variations well.

Lynman *et al.* (2010) revised their earlier study and incorporated an analysis of uncertainties in other studies by examining the effect of different methodologies used to estimate ocean heat. Their analysis focused on the period 1993 to 2008; they found ocean heat increased over this period, mostly between 2000 and 2002, but there had been negligible changes in ocean heat since 2003.

Katsman and van Oldenburgh (2011a, b) considered the period 2003–2010 and note "the upper ocean has not gained any heat, despite the general expectation that the ocean will absorb most of the Earth's current radiative imbalance." Based on an ensemble of climate models, they attributed the lack of any gain in ocean heat to ENSO events resulting in an increased loss of heat to space and increased warming in the ocean depths due to reduced northwards transport of heat in the Atlantic Ocean. This interpretation is difficult to reconcile with the behavior of ocean circulation, and especially its climatic lag effects. For example, it can take almost a decade for the heat generated by an ENSO warm event in the Pacific to travel through the Indian Ocean, around the Cape of Good Hope, and up the Atlantic to feed into the Gulf Stream (see also Section 6.2.3 below).

Gouretski *et al.* (2012) consider ocean heating since 1900, but only for the upper 400 m. They found two distinct warming periods, between 1900 and 1940–1945 and between 1970–2003. They found patterns of heating in the upper 20 m mirrored global temperature patterns and appear to include an 11-year cycle and responses to ENSO events. They also noted a distinct flattening of the ocean heating trend for the twenty-first century.

Comparing the trends determined by Levitus *et al.* for 0–2,000 m and 700–2,000 m shown in Figure 6.2.2.2.1, it is clear the upper 700 m of the ocean is more variable than the lower layer. There is no evidence of an acceleration of warming in the lower layer in the twenty-first century.

Balmaseda *et al.* (2013) attempted to account for the lack of warming in the atmosphere and upper ocean by undertaking a reanalysis of the available data and estimating the total heat content of the ocean (upper 300 m, upper 700 m, and total water column). Their method involved adjusting numerical model simulations with observational data for the period 1958–2009, which is similar to the period considered by Levitus *et al.* (2012). Balmaseda *et al.* concluded over the final decade 30 percent of the ocean heat content increase occurred below 700 m, and this increase continued despite the hiatus of warming at the surface.

The authors suggest this represents an increase in the rate of warming of the deep ocean. However, as noted by Levitus *et al.* (2012), over the period 1955–2010 about 30 percent of the warming occurred between 700 and 2000 m, indicating the result reported by Balmaseda *et al.* (2013) is not unusual. The reanalysis data produced by Balmaseda *et al.* also show a greater response to volcanic forcing and ENSO events than is evident in observational datasets, suggesting the models may be exaggerating the effect of these processes. Finally, the decadal trends estimated from model results for depths below 700 m (Table 1 of Balmaseda *et al.*, 2013) indicate decadal changes not evident in Figure 6.2.2.2.1.

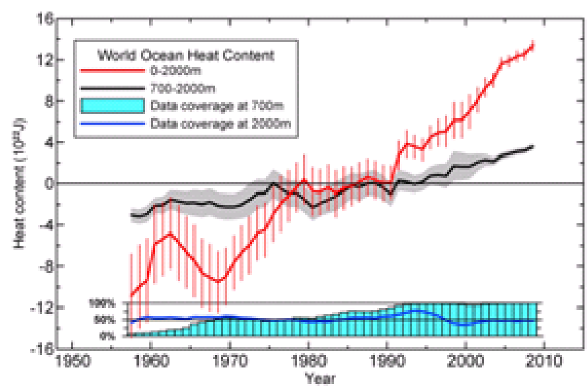

Figure 6.2.2.2.1. Smoothed (pentadal) ocean heat estimates for 0–2000 m and 700–2000 m determined by Levitus *et al.* (2012). The average temperature increases associated with the changed heat contents are 0.09°C and 0.18°C for the top 2000 m and 700 m respectively. Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., and Zweng, M.M. 2012. World ocean heat content and thermosteric sea level change (0-2000 m), 1955–2010: *Geophysical Research Letters* **39**: L10603–L10603.

Nuccitelli *et al.* (2012) presented a recalculated estimate of ocean heat content to 2,000 m between 1960 and 2008 (see Figure 6.2.2.2.2). Earlier estimates of OHC cover only the shallow ocean to 700 m and show little of the warming that is apparent in Figure 6.2.2.2.2. From their new compilation, Nuccitelli *et al.* conclude global warming is continuing. Their interpretation is at best partially valid, for several reasons.

First, Figure 6.2.2.2.2 shows warming between 2003 and 2008, when the record ends. This pattern is contradicted by the Argo profiling buoy database, which shows a flatlining or gentle cooling for 2003 to 2008. The Argo conclusion is supported by the available measurements of global sea-surface temperature, which also show cooling since 2000 (see Figure 6.2.2.2.3).

Second, no error bars are shown in Figure 6.2.2.2.2, yet they are likely to be greater than the range of change shown even for the post-2003 Argo time period; data before that date are unsystematic, with error bars so large the curve depicted is, at best, an educated guess. Third, the mechanisms that transmit incoming heat from the surface to intermediate and deep water masses have time constants of many years to centuries. Even if the depicted upper ocean warming were true, it would represent heat added to the ocean at least many decades if not centuries ago—which means it cannot have been caused by atmospheric CO_2.

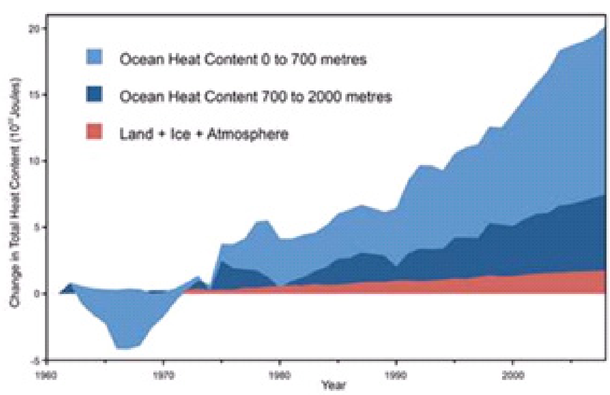

Figure 6.2.2.2.2. Ocean heat estimates. Nuccitelli, D., Way, R., Painting, R., Church, J., and Cook, J. 2012. Comment on "Ocean heat content and Earth's radiation imbalance. II. Relation to climate shifts." Physics *Letters A* **376**: 3466–3468.

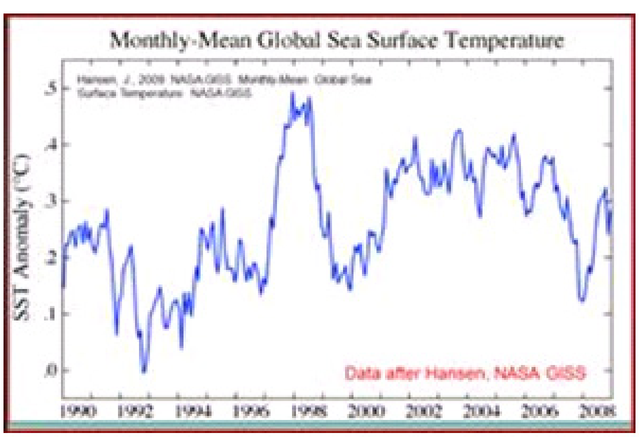

Figure 6.2.2.2.3. Mean global sea surface temperatures, 1990–2008. NASA 2008. http://data.giss.nasa.gov/ gistemp/ 2008/.

Conclusions

At the end of the twentieth century, the mild atmospheric temperature increase of the 1980s–1990s leveled off and was followed by 15 years or more of temperature stasis. Given that atmospheric carbon dioxide increased by >24 ppm over this period, this standstill poses a problem for those who argue human emissions are causing dangerous global warming.

Increasingly, this problem has been finessed by the argument that the atmosphere holds only a small percentage of the world's heat, and what really counts is the 93 percent of global heat sequestered in the oceans. Yet no sign of significant or accelerated ocean warming exists.

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6.2.3. Ocean Circulation

6.2.3.1. The Cenozoic palaeo-ocean

The high specific heat of seawater makes ocean circulation the dominant mechanism for redistributing thermal energy within Earth's climate system. Zachos *et al.* (2001) summarized the evolution of the global climate over the Cenozoic (last 65 million years) based on data obtained by the DSDP and ODP ocean drilling programmes (see Figure 6.2.3.1.1). It is evident that significant shifts in climate have been associated with major changes in ocean circulation. Major conclusions that can be drawn about ocean history from Figure 6.2.3.1.1, and the supporting references cited in Zachos *et al*. (2001), include the following:

- During the Eocene, the average temperature of the deep ocean declined by more than 7°C from ~12° C during the Eocene climatic optimum to ~4.5°C at the start of the Oligocene. This decline was associated with an increase in marine productivity, which had fallen after widespread benthic extinctions during the late Paleocene and early Eocene.

- The start of the Oligocene was associated with the opening of the Tasmania-Antarctica Passage between the Australia and Antarctic continents. This was associated with a reduction in the tropical linkages between the Pacific and Indian Oceans (strictly, their equivalents) north of Australia.

- During the Oligocene, the Drake Passage between the South America and Antarctic continents opened, allowing water to circulate around Antarctica and linking all the ocean basins. The change in ocean circulation due to the opening of the two passages was associated with the formation of an Antarctic ice cap and a further drop in deep ocean temperatures.

- The late Oligocene was marked by warming, before temperatures fell during the Miocene.

- At the start of the Pliocene the Panama Seaway between the North and South America continents closed, removing the tropical linkage between the Pacific and Atlantic Oceans. The tropical through-flow between the Pacific and Indian Oceans also was becoming more restricted. This resulted in the establishment of "modern" ocean circulation and is marked by the onset of Northern Hemisphere glaciation.

- The Pliocene and Pleistocene are characterized by glacial/interglacial climatic swings, suggesting the "modern" ocean circulation system makes Earth more sensitive to Milankovitch orbital cycles.

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Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/ science.1059412.

6.2.3.2. Modern ocean circulation

In simple terms, atmospheric and oceanic circulation systems transport excess heat from the tropics to higher latitudes—from the Equator towards the Poles. However, ocean circulation is constrained by the

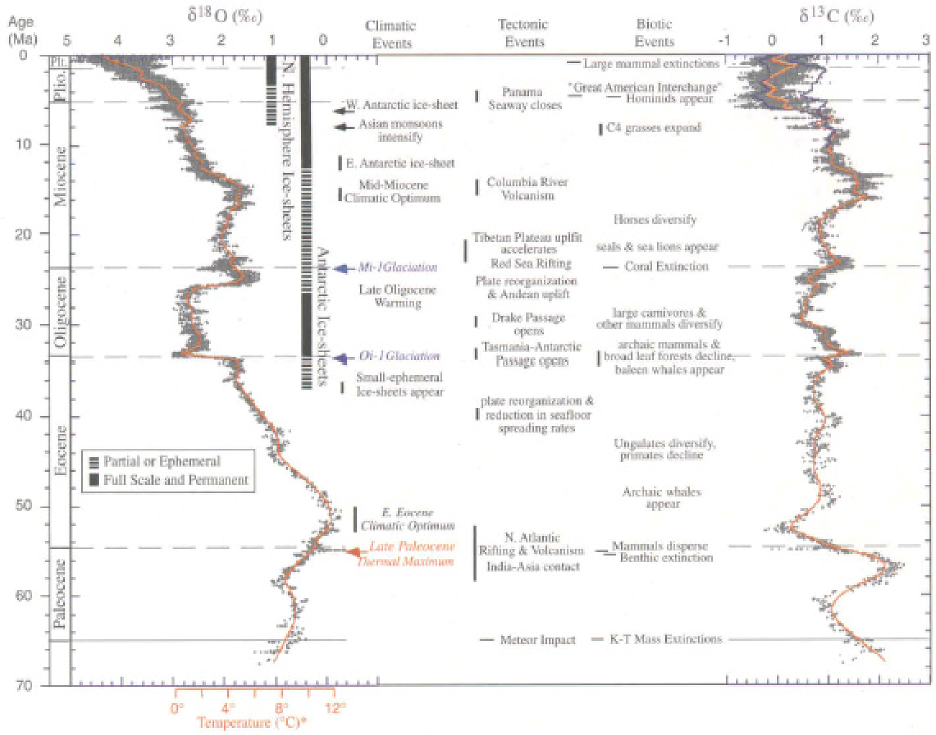

Figure 6.2.3.1.1. Summary of the major climatic, tectonic and biotic events over the last 65 million years correlated with the oxygen and carbon isotope data collected from over 40 DSDP and ODP sediment cores. Reprinted with permission from Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K. 2001. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517): 686–693. doi:10.1126/science.1059412.

configurations of ocean basins and the linkages between them. As discussed in the previous section, major changes in the basin linkages in the past have been associated with significant climatic shifts (Zachos *et al.*, 2001). The current climate is, in part, a product of the modern system of ocean circulation.

There are two main components of circulation: a surface system driven primarily by wind stress exerted by the atmosphere, and a subsurface system driven primarily by density differences associated with variations in temperature and salinity (thermohaline circulation). These two systems are linked by regions where water sinks (downwelling) and rises (upwelling) to provide a complete circulation system that eventually mixes the oceans (overturning).

A popular simplification of the combined global overturning circulation is known as the Great Ocean Conveyor Belt (see Figure 6.2.3.2.1), which emphasizes the downwelling of water in the North Atlantic to drive the thermohaline circulation and the overall transport of water back into the North Atlantic by the surface circulation driving upwelling in the Indian and Pacific Oceans (Broecker, 1991). Broecker (1997) used this concept to argue global warming could trigger abrupt climate change by slowing or stopping the downwelling of water in the North Atlantic.

The flows depicted in Figure 6.2.3.2.1, however, are unrealistic: the surface heat transport in the North Pacific is in the wrong direction, and the Indonesian through-flow is exaggerated. Schmitz (1996) presented a different version of the Great Ocean Conveyor Belt summarizing the known circulation components and their volume transport rates (see Figure 6.2.3.2.2, page 805). This diagram is difficult to conceptualize, so he prepared a perspective diagram to illustrate the relationships (see Figure 6.2.3.2.3).

Although the ocean basins are linked by circulation around Antarctic and some through-flow through the Arctic and the Indonesian Archipelago, it is evident there is also significant overturning circulation within each ocean basin. Schmitz (1996) refers to this basinal circulation as consisting of meridional overturning circulation cells.

With the exception of the South Atlantic Ocean, the cells tend to involve a net transport of warm water away from the Equator at the surface and cold water towards the Equator at depth. The South Atlantic cells produce a net transport of warm water towards the Equator, adding to the transport of warm water to the North Atlantic. Overall, there is an extra 0.5 PW (petawatt = 10^{15} W) of thermal energy transported to the North Atlantic Ocean compared to the North Pacific Ocean. This extra energy is transferred to the atmosphere as latent heat though evaporation, resulting in saltier (warm) water, which sinks and drives thermohaline circulation.

To balance the water losses associated with increased evaporation in the North Atlantic, there is increased precipitation over the North Pacific,

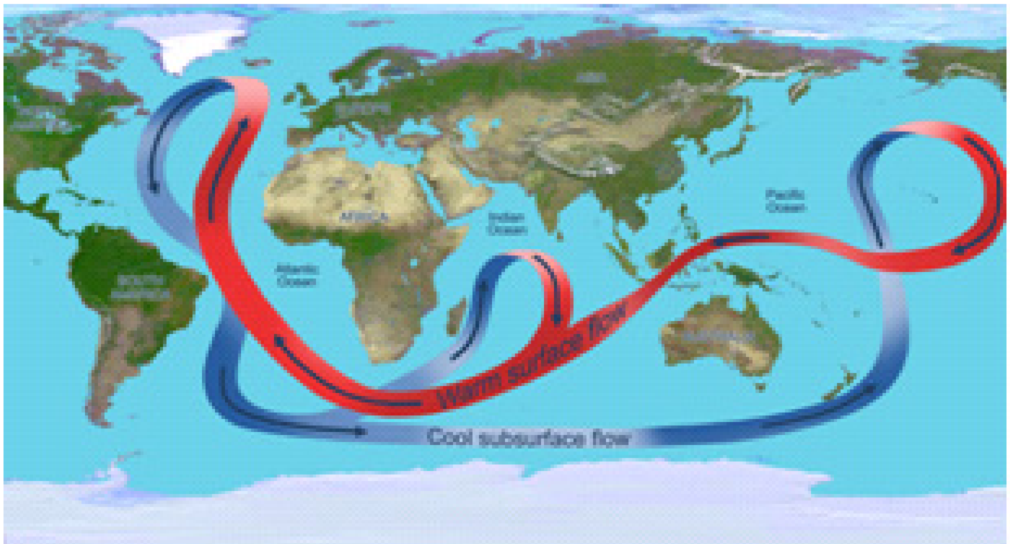

Figure 6.2.3.2.1. Simplified ocean circulation system known as the Great Ocean Conveyor Belt, highlighting the net transport of heat to the North Atlantic by surface circulation. (*http://www.jpl.nasa.gov/images/earth/ 20100325/atlantic20100325-full.jpg*).

resulting in fresher (cold) water. The component of this water that flows into the Arctic is comparatively easier to freeze than the saltier water from the North Atlantic, favoring ice formation in the Chukchi Sea over the Barents Sea.

Conclusions

Clearly, fluctuations in the supply of excess thermal energy to the North Atlantic and other oceans will have climatic consequences, and some past changes in the flow of the global ocean circulation system can be shown to be linked to major climate change; for example, flow speeds of the cold-water Pacific Deep Western Boundary Current increased during past glacial periods (Hall *et al.*, 2001). The IPCC, noting such facts, argues global warming will change the speed of major ocean circulation phenomena such as the Gulf Stream in ways that will make the world's climate less hospitable. To date, however, no published evidence exists for changes in the ocean thermohaline circulation system that lie outside the bounds of natural variation.

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6.2.3.3. Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) consists of a near-surface, warm northward flow in the Atlantic Ocean compensated by a colder southward return flow at depth (Srokosz *et al.*, 2012). A key feature is the transfer of heat to the atmosphere at high latitudes in the North Atlantic, which makes the northward-flowing surface waters saltier and cooler (denser), causing them to sink to considerable depths.

Srokosz *et al.* (2012) provide a schematic illustration of the main flows of AMOC (see Figure 6.2.3.3.1, page 806). Similar to the Great Ocean Conveyor Belt, this schematic oversimplifies the components of the circulation cell. Figure 6.2.3.3.2

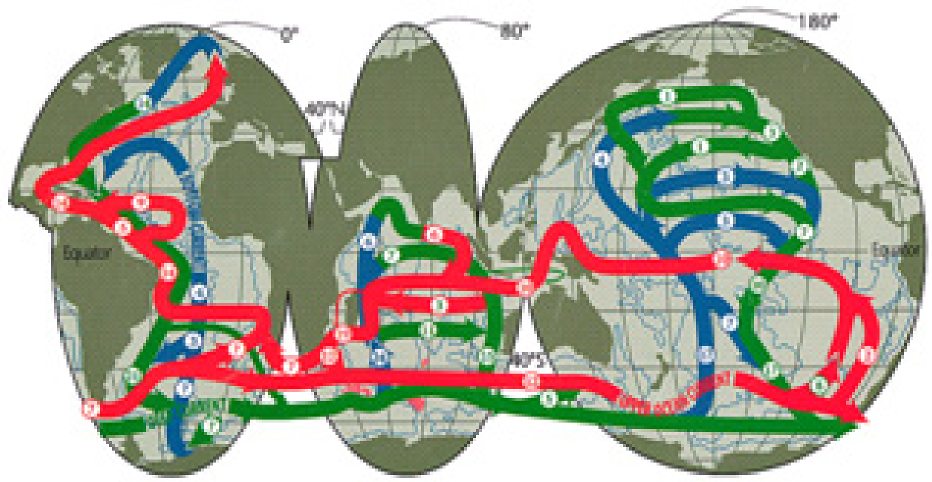

Figure 6.2.3.2.2. Summary of the main components of global ocean circulation. The volume transport rates in Sverdrups (1 Sv = 106 $m^3.s^{-1}$) are indicated in the circles. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

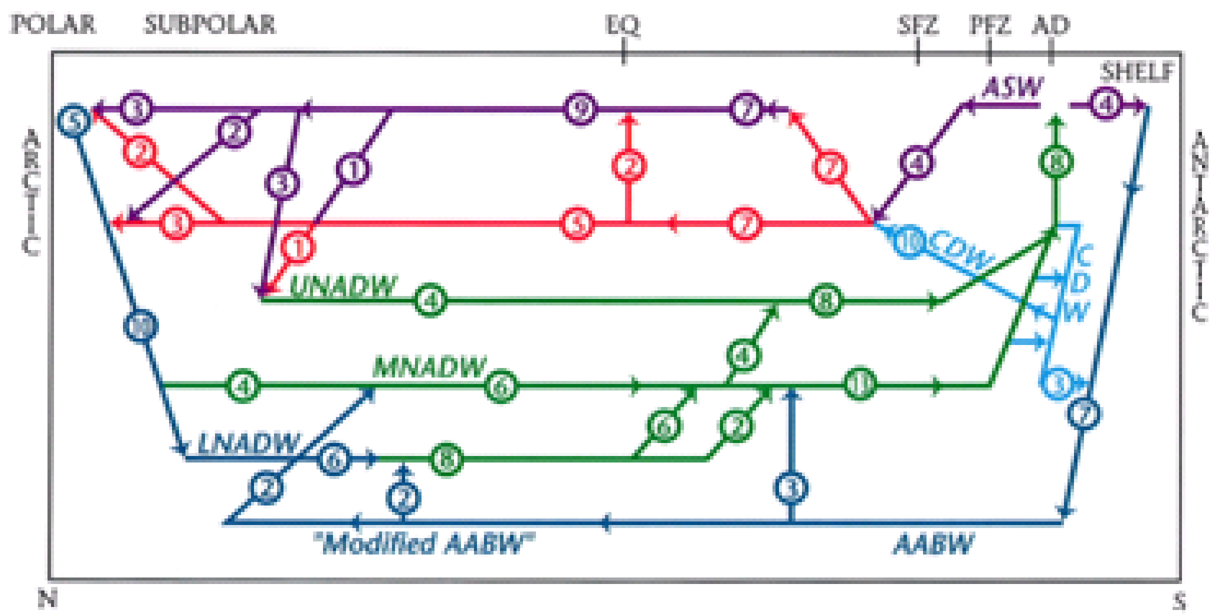

Figure 6.2.3.2.3. Components of AMOC at different depths within the Atlantic, where purple denotes an upper layer, red indicates intermediate water, green deep water, dark blue bottom, and light blue represents Circumpolar Deep Water (Schmitz, 1996). The volume transport rates for each limb are given in Sverdrups.

(on page 807), originally presented by Schmitz (1996), summarizes the major components of the circulation contributing to AMOC. This figure illustrates the deeper thermohaline circulation is also driven by water sinking around Antarctica, which means the strength of the circulation is not solely a function of the formation of dense water in the North Atlantic. There are multiple flow paths at different depths, meaning there are many different lags associated with the circulation of water masses within the system.

Baehr *et al.* (2007, 2008) used modeling to

Figure 6.2.3.3.1. Simplified model of the AMOC that regulates northern Hemisphere climate. Reprinted with permission from Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delworth, T., Lozier, S., Marotzke, J., and Sutton, R. 2012. Past, present, and future changes in the Atlantic Meridional Overturning Circulation. *Bulletin of the American Meteorological Society* **93**(11): 1663–1676. doi:10.1175/ BAMS-D-11-00151.1.

assess how quickly changes in the North Atlantic meridional overturning circulation (MOC) might flow through into consequential climate change. Simulated observations were projected onto a time-independent spatial pattern of natural variability. This variability was derived by regressing the zonal density gradient along 26°N against the strength of the MOC at 26°N, within a model-based control climate simulation. The resultant pattern was compared against observed anomalies found between the 1957 and 2004 hydrographic occupations of this latitudinal section.

The modeling revealed Atlantic MOC changes could be detected with 95% reliability after about 30 years, manifest by changes in zonal density gradients obtained from a recently deployed monitoring array. In terms of potential past changes Baehr *et al.* found "for the five hydrographic occupations of the 26°N transect, none of the analyzed depth ranges shows a significant trend between 1957 and 2004, implying that there was no MOC trend over the past 50 years."

This finding demonstrates the mild late twentieth century warming that so alarms the IPCC has not resulted in any observable change in the North Atlantic MOC. In turn, this suggests the North Atlantic MOC is not nearly as sensitive to global warming as many climate models employed by the IPCC suggest.

In a second paper addressing North Atlantic deep water formation and circulation, Vage *et al.* (2008) write, "in response to global warming, most climate models predict a decline in the Meridional Overturning Circulation, often due to a reduction of Labrador Sea Water," noting "since the mid-1990s, convection in the Labrador Sea has been shallow—and at times nearly absent."

Vage *et al.*'s paper uses Argo data, supplemented by satellite and reanalysis data, to document a return of deep convection to the subpolar gyre in both the Labrador and Irminger seas in the winter of 2007–2008. Winter mixing was observed to depths of 1,800 m in the Labrador Sea, 1,000 m in the Irminger Sea, and 1,600 m south of Greenland, whereas base-period (the winters of 2001–2006) mixing depths were less than 1,000 m. By analyzing heat flux components, Vage *et al.* determined the main cause of the enhanced heat flux and deep mixing was unusually cold air temperatures during the 2007–2008 winter. Moreover, the cooling was not merely a local phenomenon; global temperature dropped 0.45°C between the winters of 2006–2007 and 2007–2008.

Srokosz *et al.* (2012) provide a review of available research on AMOC and associated climatic variations. They highlight how poorly understood the system is; the lack of key time series data, particularly for the deeper components of AMOC; and the poor predictive abilities of computer models. From the available data, they demonstrate the recent behavior of AMOC has been surprising and unexplainable. They conclude AMOC plays a major role in climate changes, there is an urgent need for better observational data, and the behavior and potential predictability of the system need further study.

Conclusions

Studies of various parts of the global thermohaline circulation show flow rates can be quite widely variable. This variability has natural causes that have yet to be identified fully. Meanwhile, no evidence exists for additional change in ocean circulation forced by human carbon dioxide emissions.

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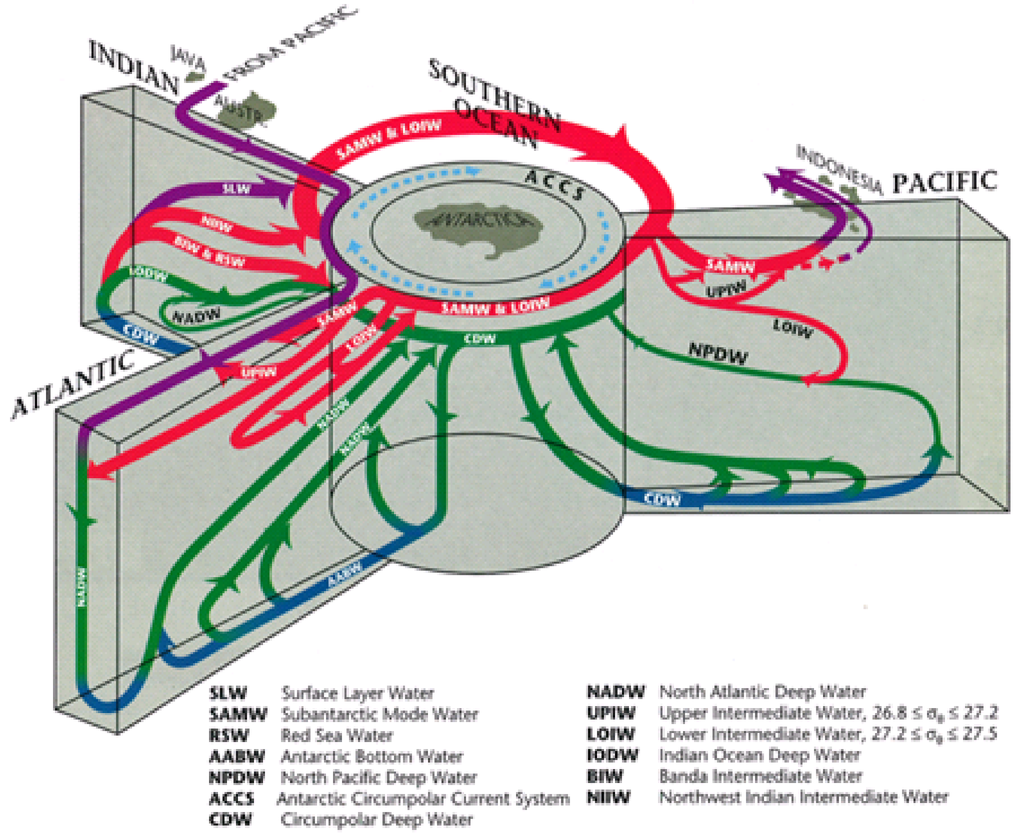

Figure 6.2.3.3.2. Summary of the main components of the global ocean circulation system. Reprinted with permission from Schmitz, W.J. 1996. *On the World Ocean Circulation: Volume II—The Pacific and Indian Oceans / A Global Update*. Technical Report, Woods Hole Oceanographic Institution, p. 245.

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7

Observations: Extreme Weather

Madhav Khandekar (Canada)

Craig Idso (USA)

Key Findings

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Key Findings

The following points summarize the main findings of this chapter:

- Air temperature variability decreases as mean air temperature rises, on all time scales.

- Therefore the claim that global warming will lead to more extremes of climate and weather, including of temperature itself, seems theoretically unsound; the claim is also unsupported by empirical evidence.

- Although specific regions have experienced significant changes in the intensity or number of extreme events over the twentieth century, for the globe as a whole no relationship exists between such events and global warming over the past 100 years.

- Observations from across the planet demonstrate droughts have not become more extreme or erratic in response to global warming. In most cases, the worst droughts in recorded meteorological history were much milder than droughts that occurred periodically during much colder times.

- There is little or no evidence that precipitation will become more variable and intense in a warming world; indeed, some observations show just the opposite.

- There has been no significant increase in either the frequency or intensity of stormy weather in the modern era.

- Despite the supposedly "unprecedented" warming of the twentieth century, there has been no increase in the intensity or frequency of tropical cyclones globally or in any of the specific ocean basins.

Introduction

For more than two decades the United Nations Intergovernmental Panel on Climate Change (IPCC) has supported the model-based narrative that carbon dioxide (CO_2)-induced global warming will cause (or is already causing) extreme weather, including more frequent and more severe heat waves, precipitation extremes (droughts and floods), storms, tropical cyclones, and other extreme weather-related events. With respect to observed changes in extreme weather, the 2012 IPCC special report on extreme weather (Field *et al*., 2012) states:

> There is evidence from observations gathered since 1950 of change in some extremes. Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning 'low confidence' in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme.

With respect to projected changes in extreme weather, that special report states:

> Confidence in projecting changes in the direction and magnitude of climate extremes depends on many factors, including the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models. … Assigning 'low confidence' for projections of a specific extreme neither implies nor excludes the possibility of changes in this extreme.

Chapter 1 of this NIPCC report presents evidence the climate models are fraught with numerous biases and shortcomings that lead to significant errors in their projections, leaving model projections highly questionable at best. Such a conclusion is especially true for projections of extreme weather events, which are much more difficult to model than average conditions and operate on much larger spatial and temporal scales. Because the models were critically examined in Chapter 1, the evaluation of their extreme weather projections will be of minor focus here. Instead, the majority of material presented in this chapter focuses on empirical observations.

More specifically, this chapter reviews historical trends in extreme weather events and examines how they interrelate with other weather and climate variables. It is clear in almost every instance of each extreme weather event examined, there is little support for predictions that CO_2-induced global warming will increase either the frequency or intensity of those events. The real-world data overwhelmingly support an opposite conclusion: Weather will more likely be less extreme in a warmer world.

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7.1 Temperature

One of the projected negative consequences of global warming is an increase in climatic variability, including more frequent extreme temperatures (mainly at the warm end of the temperature spectrum). The IPCC's *Fifth Assessment Report* claims more evidence now exists that "the AR4 conclusion that surface temperature extremes have likely been affected by anthropogenic forcing" is correct, adding "we now conclude that it is very likely that anthropogenic forcing has contributed to the observed changes in temperature extremes since the mid-20th century" (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, model projections suggest these extreme events will increase throughout this century as a consequence of CO_2-induced global warming.

It is a relatively easy matter to either substantiate or refute such claims by examining trends of extreme temperatures over the past century or so. If global warming truly has been occurring at an unprecedented rate over the past hundred years and global warming causes an increase in extreme weather events, as often claimed, temperature variability and extreme temperature events should be increasing. In the subsections of Section 7.1 that follow, we investigate this topic as it pertains to locations in Asia (7.1.1), Europe (7.1.2), North America (7.1.3), and Other Areas across the globe (7.1.4). Specifically, we present the findings of many peer-reviewed papers that do not support the IPCC claims in regard to temperature extremes.

Contrary to model projections, the studies referenced in this section indicate a warmer climate does not produce a more variable climate. The data presented herein suggest a warmer climate may very well be less variable and less extreme, if any change occurs at all. Projections of more frequent and more intense temperature extremes do not appear to be supported by the majority of scientific observations as reported in the peer-reviewed literature.

7.1.1 Asia

This subsection highlights several peer-reviewed studies from Asia that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Yadav *et al*. (2004) obtained a long tree-ring series from widely spaced Himalayan cedar trees in an effort to develop a temperature history of the western Himalayas for the period AD 1226–2000. "Since the 16th century," they write, "the reconstructed temperature shows higher variability as compared to the earlier part of the series (AD 1226–1500), reflecting unstable climate during the Little Ice Age (LIA)." They note juniper tree-ring chronologies from central Tibet provide similar results (Braeuning, 2001) and "historical records on the frequency of droughts, dust storms and floods in China also show that the climate during the LIA was highly unstable (Zhang and Crowley, 1989)." In a study of the winter half-year temperatures of a large part of China, Ge *et al*. (2003) identified greater temperature anomalies during the 1600s than in the 1980s and 1990s. Zhang and Gaston (2004) report an even greater extreme anomaly occurred in China in the summer of 1743.

This eighteenth century "heat wave attack" was felt throughout northern China, including Beijing, Tianjin, and the provinces of Hebei, Xhanxi, and Shandong. One report from Tianjin at the time said "July's heat is insupportable; fields full of cracks; rocks scorched; melting metal on mast top; many died of heat." In Gaoyi the temperature was said to be "as hot as fire in rooms and under heavy shades of trees, with melting lead and tin at midday and many died of thirst on 19–26 July." Shenze, Changzhi, Fushan, Gaoqing, and Pingyuan reported people dying from the intense heat, with the communication from Shenze saying "the disaster is indeed unprecedented." Officials reported 11,400 people died from the heat in Beijing and its suburbs between July 14 and July 25. That was a vast underestimate of the real death toll, for it included only "poor people, like craftsmen, or workers," neglecting the deaths of "the well-off and the ones in service," of which "there were a large number." And that was the death toll in the Beijing area alone.

Just how unusual was this deadly heat wave? According to Zhang and Gaston (2004), it was the hottest period of the hottest summer experienced in north China during the past seven centuries, where peak warmth exceeded the modern-day extreme heat wave high temperature by 2°C. It occurred in 1743, sandwiched between two of the coldest intervals of the Little Ice Age, as opposed to occurring during the modern era with its more-precise instruments for measuring temperature and other weather elements.

Focusing in on the modern era, Zhai and Pan (2003) derived trends in the frequencies of warm days and nights, cool days and nights, and hot days and frost days for the whole of China over the period 1951–1999, based on daily surface air temperature data obtained from approximately 200 weather observation stations scattered throughout the country.

Over the period of study, and especially throughout the 1980s and 1990s, the authors found increases in the numbers of warm days and nights, and there were decreases in the numbers of cool days and nights, consistent with an overall increase in mean daily temperature. Nevertheless, at the extreme hot end of the temperature spectrum, the authors report "the number of days with daily maximum temperature above 35°C showed a slightly decreasing trend for China as a whole." At the extreme cold end of the spectrum, the number of frost days with daily minimum temperature below 0°C declined at the rate of 2.4 days per decade. The data from approximately 200 locations across China reveal during the second half of the twentieth century there was a reduction in extreme cold weather events without any concomitant increase in extreme hot weather.

Zhou and Ren (2011) evaluated trends in 15 extreme temperature indices for the period 1961–2008 using daily temperature records from 526 measurement stations included among the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration. Based on the earlier findings of Zhou and Ren (2009)—which indicated the contribution of urban warming to overall warming often exceeded 50%—they adjusted their results to account for the impact of each site's urban heat island effect.

Zhou and Ren discovered "urbanization intensified the downward trend in cold index series and the upward trend in warm indices related to minimum temperature." They report "the urbanization effect on the series of extreme temperature indices was statistically significant for the downward trends in frost days, daily temperature range, cool nights, and cool days," as well as for "the upward trends in summer days, tropical nights, daily maximum temperature, daily minimum temperature, and warm nights." For these indices, they state "the contributions of the urbanization effect to the overall trends ranged from 10 to 100%, with the largest contributions coming from tropical nights, daily temperature range, daily maximum temperature and daily minimum temperature," adding "the decrease in daily temperature range at the national stations in North China was caused entirely by urbanization." The two researchers concluded, "more attention needs to be given to the issue [of urbanization on temperature] in future studies," something IPCC contributors and reviewers need to look at much more closely in the future than they have in the past. The urban influence can explain up to 100% of the change in extreme temperatures over the past half-century in many locations, leaving little or no room for any other influence, including CO_2-induced global warming.

Deng *et al*. (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 obtained from 10 meteorological stations to determine the number of hot days (HDs, at or above 35°C), very hot days (VHDs, at or above 38°C), and extremely hot days (EHDs, at or above 40°C) in an effort to address temperature extremes within the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. They defined a heat wave (HW) as a period with no fewer than three consecutive HDs, a short heat wave (SHW) as being at least six days long, and a long heat wave (LHW) as a heat wave exceeding six days.

Between 1958 and 2007, the three Chinese researchers reported, their study area experienced a mean annual warming trend, but with slight decreasing trends in spring and summer temperatures. Extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that "the frequencies of HWs and LHWs in the recent years were no larger than the late 1950s and early 1960s." They indicated "coupled with the extreme low frequency in the 1980s, HWs and LHWs showed a slight linear decreasing trend in the past 50 years." They found the most recent frequency of heat waves "does not outnumber 1959 or 1961," and "none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003."

Deng *et al*. conclude, "compared with the 1950s and 1960s, SHWs instead of LHWs have taken place more often," which, as they describe it, "is desirable, as longer duration leads to higher mortality," citing Tan *et al*. (2007). For the Three Gorges area of China, even a mean annual warming trend over the past half-century has not led to an increase in the frequency of extremely long heat waves.

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7.1.2 Europe

This subsection highlights several peer-reviewed studies from Europe that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Beginning with a historic view of the topic, the study of Jones and Briffa (2006), in their words, focused "on one of the most interesting times of the early instrumental period in northwest Europe (from 1730–1745), attempting to place the extremely cold year of 1740 and the unusual warmth of the 1730s decade in a longer context." The authors relied primarily on "long (and independent) instrumental records together with extensive documentary evidence," as well as "unpublished subjective circulation charts developed by the late Hubert Lamb" and "others recently developed using more objective modern reconstruction techniques."

According to the two researchers from the Climatic Research Unit of the University of East Anglia, the analysis revealed "the period 1740–1743 has been shown to be the driest period of the last 280 years, with the year 1740 the coldest recorded over the British Isles since comparable records began in 1659." They note the record cold of 1740 "is all the more remarkable given the anomalous warmth of the 1730s," which was "the warmest in three of the long temperatures series (Central England Temperature, De Bilt and Uppsala) until the 1990s occurred."

In discussing their findings, Jones and Briffa state their study "highlights how estimates of natural climatic variability in this region based on more recent data may not fully encompass the possible known range" and "consideration of variability in these records from the early 19th century, therefore, may underestimate the range that is possible." The instrumental record is simply not long enough to provide a true picture of natural temperature variability in terms of what is possible in the absence of the influence of anthropogenic greenhouse gases.

Manrique and Fernandez-Cancio (2000) employed a network of approximately 1,000 samples of tree-ring series representative of a significant part of Spain to reconstruct thousand-year chronologies of temperature and precipitation. They used the database to identify anomalies in these parameters that varied from their means by more than four standard deviations. They found the greatest concentration of extreme climatic excursions, which they describe as "the outstanding oscillations of the Little Ice Age," occurred between AD 1400 and 1600, during a period when extreme low temperatures reached their maximum frequency.

Focusing on the past century, Rebetez (2001) analyzed day-to-day variability in two temperature series from Switzerland over the period 1901–1999, during which the two sites experienced temperature increases of 1.2 and 1.5°C. Their work revealed warmer temperatures led to a reduction in temperature variability at both locations. They found "warmer temperatures are accompanied by a general reduction of variability, both in daily temperature range and in the monthly day-to-day variability," indicating even on a much finer time scale, cooling rather than warming brings an increase in temperature variability.

Beniston and Goyette (2007) noted "it has been assumed in numerous investigations related to climatic change that a warmer climate may also be a more variable climate (e.g., Katz and Brown, 1992; IPCC, 2001; Schar *et al*., 2004)" and "such statements are often supported by climate models results, as for example in the analysis of GCM and/or RCM simulated temperature and precipitation (Mearns *et al*., 1995; Mearns *et al*., 1990)." Therefore, they observed, "it is of interest to investigate whether, based on long time-series of observational data, this hypothesis is indeed verified in a climate that has experienced a warming of 2°C or more."

Noting twentieth-century warming in the alpine area of Europe "is 2–3 times greater than the global average (Jungo and Beniston, 2001) and provides an observational framework that makes it possible to address the issue of links between mean temperature and its variance," Beniston and Goyette focused their analysis on one Swiss site representative of low elevation (Basel, 369 m above sea level) and another Swiss site representative of high elevation (Saentis, 2500 m above sea level), both of which "have proven their quality in a number of previous studies (Jungo and Beniston, 2001; Beniston and Jungo, 2002; Beniston and Stephenson, 2004; Beniston and Diaz, 2004)," where they say it was determined conclusions based on data from these sites "also apply to most of the other Swiss sites."

Beniston and Goyette reported observational data since 1900 at both the low- and high-elevation sites indicate "the inter-annual and decadal variability of both maximum and minimum daily temperatures has in fact *decreased* [emphasis in the original] over the course of the 20th century despite the strong warming that has been observed in the intervening period." These findings, they added, "are consistent with the temperature analysis carried out by Michaels *et al*. (1998), where their results also do not support the hypothesis that temperatures have become more variable as global temperatures have increased during the 20th century." In addition, they found "the principal reason for this reduction in variability is related to the strong increase in the persistence of certain weather patterns at the expense of other types." Thus, the Swiss researchers reported their observations show "contrary to what is commonly hypothesized, climate variability does not necessarily increase as climate warms." They emphasized "the variance of temperature has actually decreased in Switzerland since the 1960s and 1970s at a time when mean temperatures have risen considerably."

Chase *et al*. (2006) noted much was made of the supposed uniqueness of the summer of 2003 European heat wave, its implied connection to CO_2-induced global warming, and the proposal that it was evidence of a climatic regime shift to one of greater variability that supports the more frequent occurrence of more extreme warm events (Schar *et al*., 2004; Stott *et al*., 2004; Trigo *et al*., 2005). The group of four researchers utilized NCEP global reanalysis data for the period 1979–2003 to calculate extreme tropospheric temperature events over the region 22°N to 80°N throughout the June-July-August period (and globally using annual averages), after which they compared the results with the corresponding particulars of the European heat wave of 2003 in terms of "standard deviations exceeded and correlations between regional extremes and temperatures at larger spatial scales."

Their analysis revealed "extreme warm anomalies equally, or more, unusual than the 2003 heat wave occur regularly," "extreme cold anomalies also occur regularly and can exceed the magnitude of the 2003 warm anomaly," "warmer than average years have more regional heat waves and colder than average years have more cold waves," "natural variability in the form of El Niño and volcanism appears of much greater importance than any general warming trend in causing extreme regional temperature anomalies," and "regression analyses do not provide strong support for the idea that regional heat or cold waves are significantly increasing or decreasing with time during the period considered here."

Chase *et al*. conclude their analysis "does not support the contention that similar anomalies as seen in summer 2003 are unlikely to recur without invoking a non-stationary statistical regime with a higher average temperature and increased variability." In other words, the 2003 European summer heat wave implies nothing at all about CO_2-induced global warming. It was merely a rare, but not unprecedented, weather event, of which there have been several other examples (both hot and cold, and some stronger) over the past quarter-century.

In another study conducted in an effort to understand the significance of a modern heat wave from an historical perspective, Dole *et al*. (2011) observed "the 2010 summer heat wave in western Russia was extraordinary, with the region experiencing the warmest July since at least 1880 and numerous locations setting all-time maximum temperature records." They noted "questions of vital societal interest are whether the 2010 Russian heat wave might have been anticipated, and to what extent human-caused greenhouse gas emissions played a role."

Dole *et al*. used climate model simulations and observational data "to determine the impact of observed sea surface temperatures, sea ice conditions and greenhouse gas concentrations." The nine U.S. researchers found "analysis of forced model simulations indicates that neither human influences nor other slowly evolving ocean boundary conditions contributed substantially to the magnitude of the heat wave." They observed the model simulations provided "evidence that such an intense event could be produced through natural variability alone." Similarly, they stated "July surface temperatures for the region impacted by the 2010 Russian heat wave show no significant warming trend over the prior 130-year period from 1880–2009." They noted "a linear trend calculation yields a total temperature change over the 130 years of -0.1°C." In addition, they observed "no significant difference exists between July temperatures over western Russia averaged for the last 65 years (1945–2009) versus the prior 65 years (1880–1944)" and "there is also no clear indication of a trend toward increasing warm extremes." Finally, although there was a slightly higher variability in temperature in the latter period, the increase was "not statistically significant."

"In summary," Dole *et al*. observed, "the analysis of the observed 1880–2009 time series shows that no statistically significant long-term change is detected in either the mean or variability of western Russia July temperatures, implying that for this region an anthropogenic climate change signal has yet to emerge above the natural background variability." They concluded their analysis "points to a primarily natural cause for the Russian heat wave," noting the event "appears to be mainly due to internal atmospheric dynamical processes that produced and maintained an intense and long-lived blocking event." There were no indications "blocking would increase in response to increasing greenhouse gases," the authors reported.

In a study designed to assess the extent to which temperature variability may have increased in Austria since the late nineteenth century, Hiebl and Hofstatter (2012) took a systematic and objective approach to the issue of air temperature on a local scale, based on 140 years of data from Vienna-Hohe Warte, Kremsmunster, Innsbruck-University, Sonnblick, and Graz-University.

Starting from a low level of temperature variability around 1900, the two Austrian researchers reported a slow and steady rise in variability during the twentieth century. They also reported a "period of persistently high variability levels before 1900," which led them to conclude the "relatively high levels of temperature variability during the most recent warm decades from 1990 to 2010 are put into perspective by similar variability levels during the cold late 19th century." They added, "when compared to its inter-annual fluctuations and the evolution of temperature itself, high-frequency temperature variability in the course of the recent 117–139 years appears to be a stable climate feature." Hiebl and Hofstatter concluded concerns about "an increasing number and strength of temperature extremes in terms of deviations from the mean state in the past decades cannot be maintained" and "exaggerated statements seem irresponsible."

Bohm (2012) observed "South Central Europe is among the spatially densest regions in terms of early instrumental climate data," citing Auer *et al*. (2007). He explained this fact allows for successfully testing for homogeneity and developing "a larger number of very long instrumental climate time series at monthly resolution than elsewhere," noting the resulting long time series subset of the greater alpine region provides a great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the "anthropogenic climate" of the past three decades. More specifically, he reported "the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year 'normal periods' from 1771–1800 to 1981–2010."

Bohm found "the overwhelming majority of seasonal and annual sub-regional variability trends is not significant." In the case of precipitation, for example, he observed, "there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period." Regarding temperature, he reported "most of the variability trends are insignificantly decreasing." In a "special analysis" of the recent 1981–2010 period that may be considered the first "normal period" under dominant greenhouse-gas-forcing, he found all extremes "remaining well within the range of the preceding ones under mainly natural forcing," and "in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable."

Bohm concludes "the … evidence [is clear] that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period."

Jeong *et al*. (2010) began by recognizing the model-based IPCC *Fourth Assessment Report* claim suggesting future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming, citing the work of Meehl and Tebaldi (2004) and Della-Marta *et al*. (2007). In a model-based assessment of this hypothesis, Jeong *et al*. investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments," where land surface processes are calculated by the Community Land Model (version 3) described by Oleson *et al*. (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables. The six scientists reported their calculations indicate "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included," and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." In addition, they found "the greening also tends to reduce the frequency and duration of heat waves."

Jeong *et al*. indicated just how easily the incorporation of a new suite of knowledge, in even the best climate models of the day, can dramatically alter what the IPCC and others purport to be reality, including what they say about the frequency and duration of heat waves. Yet in conjunction with their model-based work, real-world data from the past revealed extreme temperatures tend to be less frequent and less severe during warmer climatic periods than during colder ones.

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7.1.3 North America

This subsection highlights several peer-reviewed studies from North America that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Shabbar and Bonsal (2003) examined trends and variability in the frequency, duration, and intensity of winter cold and warm spells in Canada during the second half of the twentieth century. For the period 1950–1998, they found western Canada experienced decreases in the frequency, duration, and intensity of winter cold spells. In the east, however, distinct increases in the frequency and duration of winter cold spells occurred. With respect to winter warm spells, significant increases in both their frequency and duration were observed across most of Canada, with the exception of the extreme northeastern part of the country, where warm spells appear to be becoming shorter and less frequent. In the mean, therefore, there appear to be close-to-compensating trends in the frequency and intensity of winter cold spells in different parts of Canada, while winter warm spells appear to be increasing somewhat.

Khaliq *et al*. (2007) noted "extreme climate events are receiving increased attention because of the possibility of increases in their frequency and severity in future climate as a result of enhanced concentrations of greenhouse gases in the atmosphere and associated atmospheric warming" and "transient climate change simulations performed with both Global Climate Models and Regional Climate Models suggest increased frequencies of extreme high temperature events." The five researchers assessed temporal changes in the frequency of occurrence and durations of heat waves based on data acquired at seven weather stations located in southern Quebec for the 60-year period 1941–2000. For heat spells defined in terms of daily maximum air temperature, the majority of extreme events showed "a negative time-trend with statistically significant decreases (at 10% level)," while almost all of the heat spells defined in terms of daily minimum air temperature showed "a positive time-trend with many strong increases (i.e., statistically significant at 5% level) at all of the stations." Khaliq *et al*. stated "a possible interpretation of the observed trends is that the maximum temperature values are getting less hot and minimum temperature values are getting less cold with time," signaling a reduction in overall temperature variability.

Bonsal *et al*. (2001) reported similar findings several years earlier, analyzing spatial and temporal characteristics of daily and extreme temperature-related variables across Canada over the period 1900–1998. They found "significant trends toward fewer days with extreme low temperature during winter, spring, and summer" as well as "trends toward more days with extreme high temperature in winter and spring," but noted "these are not as pronounced as the decreases to extreme low values." They found "no indication of any consistent changes to the magnitude of extreme high daily maximum temperature during summer" and "in general, day-to-day temperature variability has decreased over most of southern Canada during the twentieth century," evidenced by a greater increase in daily minimum (as opposed to maximum) extreme temperature values.

Taking a much longer view of the subject, Fallu *et al*. (2005) derived a 6,700-year temperature history for northern Quebec, Canada. They found after an initial increase in temperature that lasted from 6400 to 4900 cal. yr BP, a warm phase occurred from 4900 to ca. 1500 cal. yr BP. They reported the data obtained from this latter portion of the sediment core "suggest the most stable paleoclimatic conditions during this period." Then came what they call the "recent cooling," which lasted from ca. 1500 cal. yr BP to modern times, during which interval, they found, "lake water temperature apparently became increasingly unstable." Accordingly, temperature variability in this region declined when the climate warmed.

Kunkel *et al*. (1999) investigated the occurrence of intense heat and cold waves from 876 locations in the southwestern United States over the period 1931–1997. They found a decline in exceedance probability threshold since 1930 for heat waves, and no trend was identified for cold spells (see Figures 7.1.3.1 and 7.1.3.2). As a result of these and other findings, Kunkel *et al*. concluded there has been "no evidence of changes in the frequency of intense heat or cold waves."

Iskenderian and Rosen (2000) studied two mid-tropospheric temperature datasets spanning the past 40 years, calculating day-to-day variability within each month, season, and year. Averaged over the entire Northern Hemisphere, they found mid-tropospheric temperature variability exhibited a slight upward trend since the late 1950s in one of the datasets, but "this trend is significant in the spring season only." They also admitted "the robustness of this springtime trend is in doubt" because the trend obtained from the other dataset was negative. For the conterminous United States, the two datasets showed "mostly small positive trends in most seasons" but none of these trends were statistically significant. Iskenderian and Rosen acknowledged they "cannot state with confidence that there has been a change in synoptic-scale temperature variance in the mid-troposphere over the United States since 1958."

Two years later, in a study based on daily maximum (max), minimum (min), and mean air temperatures (T) from 1062 stations of the U.S. Historical Climatology Network, Robeson (2002) computed the slopes of the relationships defined by plots of daily air temperature standard deviation vs. daily mean air temperature for each month of the year for the period 1948–1997. This protocol revealed, in Robeson's words, "for most of the contiguous USA, the slope of the relationship between the monthly mean and monthly standard deviation of daily Tmax and Tmin—the variance response—is either negative or near-zero." This means, as he described it, "for

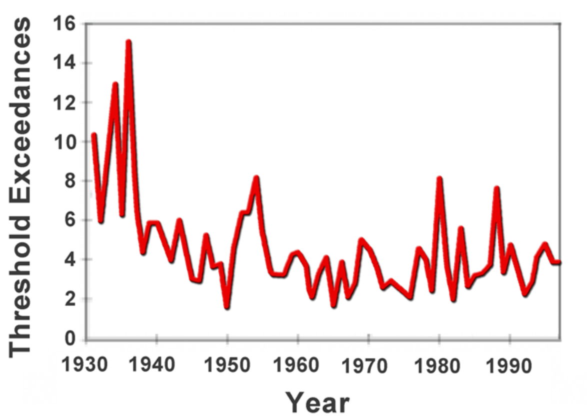

Figure 7.1.3.1. Heat wave exceedance threshold calculated as the number of days with a maximum temperature above the threshold for a 1.5% daily exceedance probability. The curve represents an average of 876 long-term stations in the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098.

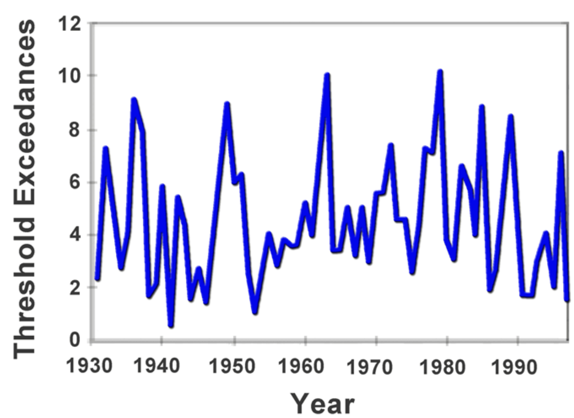

Figure 7.1.3.2. Cold wave exceedance threshold calculated as the number of days with a minimum temperature below the threshold for a 98.5% daily exceedance probability. The curve represents an average of 876 long-term stations from the USA. Adapted from Kunkel, K.E., Pielke Jr., R.A., and Changnon, S.A. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* **80**: 1077–1098..

most of the contiguous USA, a warming climate should produce either reduced air-temperature variability or no change in air-temperature variability." He also reported the negative relationships are "fairly strong, with typical reductions in standard deviation ranging from 0.2 to 0.5°C for every 1°C increase in mean temperature."

DeGaetano and Allen (2002b) created a Daily Historical Climatology Network for Extreme Temperature (HCN-XT) dataset (DeGaetano and Allen, 2002a), which they used to determine how both hot and cold temperature extremes—defined in terms of the number of exceedances of the 90th, 95th, and 99th%iles of their respective databases—have varied across the contiguous United States over a number of different time scales.

Over the period 1960–1996, DeGaetano and Allen determined "a large majority of stations show increases in warm extreme temperature exceedances," which would seem to corroborate model-based claims. They also reported "about 20% of the stations experience significant increases in warm maximum temperature occurrence," again in seeming vindication of model-based claims. Furthermore, they noted "similar increases in the number of ≥2 and ≥3 runs of extreme temperatures occur across the country," apparently substantiating claims of an increasing frequency of deadly heat waves.

However, when the two scientists extended their analyses further back in time, they obtained quite different results. Adding another 30 years of data onto the front ends of their databases, DeGaetano and Allen discovered there were "predominantly decreasing warm exceedance trends across the country during the 1930–96 period." They found "in the 1930–96 period 70% of the stations exhibit decreasing high extreme maximum temperature trends."

DeGaetano and Allen also found "trends in the occurrence of maximum and minimum temperatures greater than the 90th, 95th, and 99th%ile across the United States are strongly influenced by urbanization." With respect to daily warm minimum temperatures, for example, the slope of the regression line fit to the data of a plot of the annual number of 95th%ile exceedances vs. year over the period 1960–96 was found to be +0.09 exceedances per year for rural stations, +0.16 for suburban stations, and +0.26 for urban stations, making the rate of increase in extreme warm minimum temperatures at urban stations nearly three times greater than the increase at rural stations less affected by growing urban heat islands. The rate of increase in the annual number of daily maximum temperature 95th%ile exceedances per year over the same time period was found to be 50% greater at urban stations than at rural stations. In spite of this vast uncorrected bias, when computed over the longer 1930–1996 period, 70% of all stations in the HCN-XT dataset exhibited "decreasing high extreme maximum temperature trends."

DeGaetano and Allen's findings clearly show extreme warm temperature events over the USA are no more prevalent currently than they were in the 1930s and may be even less prevalent now. Also, there is strong evidence implicating the growing influence of intensifying urban heat islands as being responsible for the apparent rapid increase in the mean annual temperatures for many locations over the last two decades of the twentieth century. Thus, even for the part of the world that may have experienced some net warming over the past 70 years, the warming is likely minimal.

Focusing on extreme temperatures experienced during heat waves, Redner and Petersen (2006) noted "almost every summer, there is a heat wave somewhere in the United States that garners popular media attention," and it is only natural to wonder if global warming played a role in producing it. The two scientists set out to investigate "how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures," after which they assessed the potential of global warming to produce such temperatures by comparing their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia.

The two researchers concluded "the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data." They found they "cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures," even with 126 years of real-world data. Such findings suggest it is not statistically justifiable to attribute any individual heat wave or "proliferation of record-breaking temperature events" to historical global warming, be it CO_2-induced or otherwise.

In an attempt to determine the role the planet's mean temperature may have played in influencing temperature variability during the latter half of the twentieth century, Higgins *et al.* (2002) examined the influence of two important sources of Northern

Hemispheric climate variability—the El Niño/ Southern Oscillation (ENSO) and the Arctic Oscillation—on winter (Jan–Mar) daily temperature extremes over the conterminous United States from 1950 to 1999. With respect to the Arctic Oscillation, there was basically no difference in the number of extreme temperature days between its positive and negative phases. With respect to the ENSO phenomenon, however, Higgins *et al*. found during El Niño years, the total number of extreme temperature days decreased by approximately 10%, while during La Niña years they increased by approximately 5%. With respect to winter temperatures throughout the conterminous United States, therefore, the model-based contention that warmer global temperatures—such as are typically experienced during El Niño years—will produce more extreme weather conditions is unsupported, as Higgins *et al* found the opposite to be true.

Contrary to model projections, the research reported here concludes a warmer climate does not tend to produce a more variable climate. The data suggest a warmer climate may be less variable and less extreme, if any change occurs at all. The scientific literature does not support projections of more frequent and intense summer heat waves.

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7.1.4 Other Areas

This subsection highlights several peer-reviewed studies from various other regions of the globe (outside of Asia, Europe, and North America, examined in the preceding subsections) that do not support the IPCC-based claim that CO_2-induced global warming is bringing, or will bring, an increase of temperature variability or temperature extremes.

Starting with a long temporal view of the subject, Oppo *et al*. (1998) studied sediments from Ocean Drilling Project site 980 on the Feni Drift (55.5°N, 14.7°W) in the North Atlantic. Working with a core formed 500,000 to 340,000 years ago, they analyzed $\delta^{18}O$ and $\delta^{13}C$ obtained from benthic foraminifera and $\delta^{18}O$ obtained from planktonic foraminifera to develop histories of deep water circulation and sea surface temperature (SST), respectively. They discovered a number of persistent climatic oscillations with periods of 6,000, 2,600, 1,800, and 1,400 years that traversed the entire length of the sediment core record, extending through glacial and interglacial epochs alike. These SST variations, which were found to be in phase with deep-ocean circulation changes, were on the order of 3°C during cold glacial maxima but only 0.5 to 1°C during warm interglacials.

McManus *et al*. (1999), who also examined a half-million-year-old deep-sea sediment core from the eastern North Atlantic, reported similar findings. The authors noted significant SST oscillations throughout the record, and they too were of much greater amplitude during glacial periods (4 to 6°C) than during interglacials (1 to 2°C). Likewise, in another study of a half-million-year-long sediment core from the same region, Helmke *et al*. (2002) found the most stable of all climates held sway during what they called "peak interglaciations" or periods of greatest warmth. The temperatures in each of the interglacials that preceded our current interglacial were warmer than the present one, and by an average temperature in excess of 2°C, as determined by Petit *et al*. (1999). Thus, even if Earth were to continue its recent recovery from the global chill of the Little Ice Age, that warming likely would cause a decrease in temperature variability, as evidenced by real-world data pertaining to the past half-million years.

Shifting the temporal focus to that of the past millennium, Cook *et al*. (2002) reported the results of a tree-ring study of long-lived silver pines on the West Coast of New Zealand's South Island. The chronology they derived provided a reliable history of Austral summer temperatures from AD 1200 to 1957, after which measured temperatures were used to extend the history to 1999. Cook *et al*. stated their reconstruction showed "there have been several periods of above and below average temperature that have not been experienced in the 20th century," indicating New Zealand climate was much less variable over the last century than it was over the prior 700 years.

Focusing on a finer temporal resolution, Ault *et al*. (2009) employed 23 coral $\delta^{18}O$ records from the Indian and Pacific Oceans to extend the observational record of decadal climate variability in the region to AD 1850–1990, noting "coral records closely track tropical Indo-Pacific variability on interannual to decadal timescales (Urban *et al*., 2000; Cobb *et al*., 2001; Linsley *et al*., 2008)." The seven scientists identified "a strong decadal component of climate variability" that "closely matches instrumental results from the 20th century." In addition, they noted the decadal variance was much greater between 1850 and 1920 than it was between 1920 and 1990. The researchers "infer that this decadal signal represents a fundamental timescale of ENSO variability" whose enhanced variance in the early half of the record "remains to be explained."

In a study designed to investigate the IPCC contention "that in the future the frequency of extreme temperature events and their magnitude will increase," Rusticucci and Barrucand (2004) investigated how such a claim might apply to Argentina, deriving trends of the mean, the standard deviation, and the extreme maximum and minimum daily temperatures over the period 1959–1998 based on "a deeply quality-controlled stations database." According to the two Argentine scientists, "the variable that presents the largest number of stations with observed significant trends is the minimum temperature in summer, where positive trend values were found at many stations over 4°C (100 yr)$^{-1}$." They also reported "the maximum temperature in summer presented strong negative values of the same magnitude in stations located in central Argentina." The researchers concluded "a large fraction of the area that yields most of the agricultural production of Argentina should result in reduced air temperature variability in the case of a warming climate, as is also shown by Robeson (2002) for the United States."

Rusticucci (2012) further examined the claim global warming will increase climatic variability, reviewing many studies that have explored this subject throughout the length and breadth of South America, particularly as it applies to daily maximum and minimum air temperatures. The Buenos Aires researcher found the most significant trends exist in the evolution of the daily minimum air temperature, with "positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature)," as well as negative trends in the cold extremes of the minimum temperature. She states this was the case "in almost all studies." By contrast, she writes, "on the maximum temperature behavior there is little agreement, but generally the maximum temperature in South America has decreased."

In general, over most of South America there has been a decrease in the extremeness of both daily maximum and minimum air temperatures, with the maximums declining and the minimums rising. These findings are beneficial, as Rusticucci notes cold waves and frost are especially harmful to agriculture, one of the main economic activities in South America. Cold waves and frost days were on the decline nearly everywhere throughout the continent during the warming of the twentieth century.

Alexander *et al*. (2006) developed what they call "the most up-to-date and comprehensive global picture of trends in extreme temperature." They analyzed results from a number of workshops held in data-sparse regions and high-quality station data supplied by numerous scientists from around the world, after which several seasonal and annual temperature indices for the period 1951–2003 were calculated and gridded, and trends in the gridded fields were computed and tested for statistical significance.

Alexander *et al*. report "over 70% of the land area sampled showed a significant increase in the annual occurrence of warm nights while the occurrence of cold nights showed a similar proportion of significant decrease," with some regions experiencing "a more than doubling of these indices." At the other end of the scale, they found only 20% of the land area sampled exhibited statistically significant changes, specifically noting "maximum temperature extremes have also increased but to a lesser degree." These findings, in the words of the researchers, "agree with earlier global studies (e.g., Jones *et al*., 1999) and regional studies (e.g., Klein Tank and Konnen, 2003; Manton *et al*., 2001; Vincent and Mekis, 2006; Yan *et al*., 2002), which imply that rather than viewing the world as getting hotter it might be more accurate to view it as getting less cold."

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7.1.5 Cold Weather Extremes

The global mean temperature trend, estimated by the UK Met Office, shows a lack of warming of Earth's climate during the past 16 years. In addition, there is mounting evidence of a recent increase in cold weather extremes in many parts of the world.

The brunt of recent cold weather extremes seems to have been borne by Europe, which has experienced extremely cold winters for the past six years. The latest round of cold European weather (in 2013) brought large amounts of snow in northern France, Germany, Belgium, and Poland. Berlin is reported to have experienced its coldest winter in 100 years. Also, Hungary and Poland reported excessive snow and bitterly cold weather in the month of March. Just last year (February 2012) most of eastern and Central Europe, including Belarus, Poland, Slovakia, and the Czech Republic, experienced severe cold weather, with low temperatures at some locales reaching -40°C and below. The cold weather caused several hundred deaths during February 2012 in the Czech Republic, Hungary, and Poland.

The winters of 2009–2010 and 2010–2011 were equally cold and snowy in parts of Europe and North America (Seager *et al*., 2010; Taws *et al*., 2011). In South America, winters have become colder during the past six years. In July 2007, parts of Argentina reported low temperatures at -25°C, and snow fell in Buenos Aires in July 2007 – the city's first snowfall since 1918. July 2013 was significantly colder in the southern regions of South America, with snow reported in more than 75 locales in Argentina and southern Brazil during the week of July 20–25, 2013.

In tropical Asia, winters also have become colder in the past ten years. The severity of the cold winter of 2002–2003 was felt as far south as Vietnam and Bangladesh, where several hundred people died of exposure. Also, winters in Northern India have become colder in the past six years or so. The past winter (December 2012–January 2013) brought several low temperature records (0°C to -5°C) in parts of NW India and in many large cities such as New Delhi, which endured its coldest January in 40 years. Several hundred people died from exposure to the cold weather there as well, as houses in North India are not equipped with heating or good insulation.

The media rarely mention such extreme cold weather events, and the past few years have brought relatively few studies on cold winters. Most such publications have been by European meteorologists and climate scientists. Among the papers reported in recent literature are those by Benested (2010), Cattiauax *et al*. (2010), Haigh (2010), Lockwood *et al*. (2011), Petoukhov and Semenov (2010), Sirocko *et al*. (2012), Wang *et al*. (2010), and Woollings *et al*. (2010). Many of these papers suggest reduced solar activity played a prominent role in the observed colder winters.

Some solar scientists are investigating the possibility of the Sun entering into a Grand Solar Minimum (GSM), which could manifest itself within two decades (Lockwood *et al*., 2011). How an approaching GSM might impact Earth's climate is being studied extensively. Papers by Schindell *et al*., (2001) and others discussed the impact of past low solar activity on regional and global climate. During the last GSM, known popularly as the Maunder Minimum, Earth's climate underwent what has come to be known in climatic terms as the Little Ice Age (LIA), a period that brought the coldest temperatures of the Holocene, or current interglacial, in which we live. Lasting about 200 years (approximately 1650–1850), the brunt of the LIA was felt in Europe, which experienced long and extreme winters and cooler summers. Soon and Yaskell (2003) provide a comprehensive discussion of the climatic impact of the Maunder Minimum. Whether the Sun is indeed approaching a new Grand Solar Minimum, however, remains to be seen.

Along with a recent spate of cold temperature extremes experienced across the globe, record snowfall has occurred in many places, especially in the Northern Hemisphere. The winter of December 2012–March 2013 brought several large snowstorms across Europe and North America. The first two weeks of March saw several heavy to very heavy snowfalls in Northern France, Germany, and Belgium, with snowfall amounts reaching 25cm and more in many places. Over North America, the winter of 2012–2013 was long and snowy from the southwestern U.S. to the upper Midwest. A February 26–27 snowstorm dumped more than 45cm of snow on Amarillo, Texas. The same storm dumped more than 30 cm of snow on parts of central Ontario and Toronto as it moved in a SW-NE track. In early to mid-March, snowfalls varying from 20cm to 30cm fell in several states from Colorado to Minnesota. On the Canadian Prairies, the week of March 17–24 saw heavy snowfalls (15–25cm) in parts of Alberta and Saskatchewan.

Other examples of recent heavy snowfall include:

Winter 2011–2012:

Alaska. Some of the heaviest snowfalls ever recorded fell in January 2012. The fishing community of Cordova (east side of Prince William Sound) received close to 450cm of snow between November 2011 and January 2012. At Valdez, more than 350cm of snow fell in the first two weeks of January.

Canadian Rockies. The Canadian Rockies experienced some of the region's heaviest-ever recorded snowfalls in many areas. Sunshine Village (a popular ski resort on the Alberta/British Columbia border) set an all-time record with more than 915cm of snow by March 25. At Mount Norquay (near Banff, Alberta) more than 900cm of snow fell from November to March. At Ferni Alpine Resort (British Columbia) more than 1,000cm of snow fell during the 2011–2012 winter season, a record.

Europe. One of the most severe winters in Eastern Europe brought snowfalls of 25cm and more. In the eastern Adriatic Sea, more than 35cm of snow fell near Montenegro on February 10–11.

Japan. Snowfall several tens of cm deep fell in parts of Japan during February 12–14, 2012.

Winter 2010–2011: More than 80cm of snow fell in a two-day period (5–6 December 2010) in London, Ontario (Canada). Montreal received more than 30cm (December 6–7).

Winter 2009-2010: The largest snow cover extent in the history of the contiguous United States occurred in December 2009. The mid-Atlantic cities of Baltimore, Philadelphia, and Washington, DC had their snowiest winters ever (each received more than 150cm of snow). The winter of 2009–2010 was the snowiest since 1977–78 in the Northern Hemisphere. Khandekar (2010) reported additional snowfall and cold weather records during the previous 10 years.

The latest snow cover data archived at the Rutgers Northern Hemisphere snow data center (US) are shown in Table 7.1.5.1. The winter of 2012–2013 was the fourth snowiest in Northern Hemisphere history. Five winter seasons (December–February) since 2000 are among the top six winters for snow accumulation. If the November snow data were included in the table, this past winter would be the second snowiest winter during the past 40 years.

Winter snow accumulation in the Northern Hemisphere has been increasing in recent years. Such observations run counter to model projections suggesting there should be less snowfall occurring in response to CO_2-induced global warming.

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Table 7.1.5.1. The top 15 winter season snowfall accumulation totals in the Northern Hemisphere.

Season (Dec–Feb)	Snow Accumulation (Millions km^2)
1977–78	48.403
2009–10	47.507
2010–11	47.183
2012–13	47.150
2007–08	46.910
2002–03	46.830
1978–79	46.730
1984–85	46.722
1985–86	46.577
1971–72	46.517
1970–71	46.317
1968–69	46.297
1966–67	46.073
1981–82	45.810
2011–12	45.803

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7.2 Heat Waves

In response to an increase in mean global air temperature, the IPCC contends there will be more frequent and severe extremes of various weather phenomena, including more frequent and extreme heat waves. In its *Fifth Assessment Report*, the IPCC states "models also project increases in the duration, intensity and spatial extent of heat-waves and warm spells for the near term" (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). Furthermore, they suggest an anthropogenic influence is already underway, stating "we now conclude that it is likely that human influence has significantly increased the probability of some observed heat waves" (p. 31 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). Although much of the material in the preceding section of this chapter (Section 7.1, Temperature) reveals the IPCC claims on heat waves have little support in the scientific literature, this section examines additional studies that also explain why the IPCC projections are likely wrong.

Deng *et al*. (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 to examine trends in heat waves in the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. The three Chinese researchers report their study area experienced a mean annual warming trend with slight decreasing trends in spring and summer temperatures. They also found extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the twenty-first century, such that "the frequencies of heat waves and long heat waves in the recent years were no larger than the late 1950s and early 1960s." They observed, "coupled with the extreme low frequency in the 1980s, heat waves and long heat waves showed a slight linear decreasing trend in the past 50 years." They noted the most recent frequency of heat waves "does not outnumber 1959 or 1961" and "none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003."

Deng *et al*. concluded, citing Tan *et al*. (2007), "compared with the 1950s and 1960s, short heat waves instead of long heat waves have taken place more often," which, as they describe it, "is desirable, as longer duration leads to higher mortality."

Redner and Petersen (2006) investigated "how systematic climatic changes, such as global warming, affect the magnitude and frequency of record-breaking temperatures." They compared their predictions to a set of Monte Carlo simulation results and to 126 years of real-world temperature data from the city of Philadelphia. The results of their mathematical analysis led them to conclude "the current warming rate is insufficient to measurably influence the frequency of record temperature events, a conclusion that is supported by numerical simulations and by the Philadelphia data." They also stated they "cannot yet distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures," even with 126 years of data.

Fischer *et al*. (2007) and Robock *et al*. (2000) may provide some insight into why the models are failing in their heat wave projections.

Fischer *et al*. conducted regional climate simulations, both with and without land-atmosphere coupling, for the major European summer heat waves of 1976, 1994, 2003, and 2005. The authors found during all simulated heat wave events, "soil moisture-temperature interactions increase the heat wave duration and account for typically 50–80% of the number of hot summer days," noting "the largest impact is found for daily maximum temperatures," which were amplified by as much as 2-3°C in response to observed soil moisture deficits in their study.

Robock *et al*. developed a massive collection of soil moisture data from more than 600 stations spread across a variety of climatic regimes (including the former Soviet Union, China, Mongolia, India, and the United States). They found "for the stations with the longest records, summer soil moisture in the top 1 m has increased while temperatures have risen." This counterintuitive finding was confirmed by Robock *et al*. (2005) and Li *et al*. (2007), the latter noting when exposed to elevated concentrations of atmospheric CO_2, "many plant species reduce their stomatal openings, leading to a reduction in evaporation to the atmosphere," so "more water is likely to be stored in the soil or [diverted to] runoff." Gedney *et al*. (2006) confirmed the latter phenomenon. Pearce (2006) quoted Gedney saying "climate change on its own would have slightly reduced runoff, whereas the carbon dioxide effect on plants would have increased global runoff by about 5%," with the combined effect of the two competing phenomena leading to the 3–4% flow increase actually observed.

In light of the complementary global soil moisture and river runoff observations, it would appear, in general, the anti-transpiration effect of the historical rise in the air's CO_2 content has more than compensated for the soil-drying effect of global warming. Fischer *et al*. (2007) found soil moisture depletion greatly augments both the intensity and duration of summer heat waves, while Robock *et al*. (2000, 2005) and Li *et al*. (2007) found global soil moisture has increased over the past half-century, likely as a result of the anti-transpiration effect of atmospheric CO_2 enrichment—as Gedney *et al*. (2006) also have found to be the case with closely associated river runoff. Thus the increase in soil moisture caused by rising atmospheric CO_2 concentrations will tend to decrease both the intensity and duration of summer heat waves as time progresses. That relationship may explain why historic heat waves in locations such as Philadelphia and the Three Gorges area of China have not increased in response to what the IPCC often refers to as the unprecedented warming of the late twentieth and early twenty-first centuries.

Jeong *et al*. (2010) observe modeling studies in the IPCC's *Fourth Assessment Report* (AR4) suggest future heat waves over Europe will be more severe, longer-lasting, and more frequent than those of the recent past, due largely to an intensification of quasi-stationary anticyclone anomalies accompanying future warming. Jeong *et al*. investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments," where land surface processes were calculated by the Community Land Model (version 3) described by Oleson *et al*. (2004), which includes a modified version of the Lund-Potsdam-Jena scheme for computing vegetation establishment and phenology for specified climate variables.

Their calculations revealed "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included," and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapo-transpiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." The scientists found "the greening also tends to reduce the frequency and duration of heat waves."

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7.3 Fire

According to model-based predictions, larger and more intense wildfires will become more frequent as a result of CO_2-induced global warming. Many scientists have begun to search for a link between fire and climate, often examining past trends to see if they support the models' projections. The following section examines what has been learned in this regard, beginning with a review of studies conducted in North America and ending with a discussion of the planet as a whole.

Campbell and Campbell (2000) analyzed pollen and charcoal records obtained from sediment cores retrieved from three small ponds—South Pond (AD 1655–1993), Birch Island Pond (AD 1499–1993), and Pen 5 Pond (400 BC–AD 1993)—in Canada's Elk Island National Park, which covers close to 200 km^2 of the Beaver Hills region of east-central Alberta. "Counter to the intuitive increase in fire activity with warmer and drier climate," the Canadian researchers reported, "declining groundwater levels during the Medieval Warm Period [MWP] allowed the replacement of substantial areas of shrub birch with the less fire-prone aspen, causing a decline in fire frequency and/or severity, while increasing carbon storage on the landscape," as implied by their Pen 5 Pond data. They concluded this scenario "is likely playing out again today," as all three of the sites they studied "show historic increases in *Populus* pollen and declines in charcoal."

Carcaillet *et al*. (2001) developed high-resolution charcoal records from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada. The scientists determined whether vegetation change or climate change was the primary determinant of changes in fire frequency, comparing their fire history with hydroclimatic reconstructions derived from $\delta^{18}O$ and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago, when it was significantly warmer than it is today, they reported "fire intervals were double those in the last 2,000 years," meaning fires were only half as frequent throughout the earlier, warmer period as they were during the subsequent, cooler period. They also determined "vegetation does not control the long-term fire regime in the boreal forest," but instead, "climate appears to be the main process triggering fire." In addition, they report "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al*., 1990; Larsen, 1997; Weir *et al*., 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al*., 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)." The scientists concluded a "future warmer climate is likely to be less favorable for fire ignition and spread in the east Canadian boreal forest than over the last 2 millennia."

Le Goff *et al*. (2007) investigated "regional fire activity as measured by the decadal proportion of area burned and the frequency of fire years vs. non-fire years in the Waswanipi area of northeastern Canada [49.5–50.5°N, 75–76.5°W], and the long-term relationship with large-scale climate variations ...

using dendroecological sampling along with forest inventories, aerial photographs, and ecoforest maps." Their analysis showed instead of the interval of time between wildfires shortening as time progressed and the climate warmed, there was "a major lengthening of the fire cycle," which expanded "from 99 years before 1940 to 282 years after 1940." In addition, Le Goff *et al*. noted "in the context of the past 300 years, many regional fire regimes of the Canadian boreal forest, as reconstructed from dendroecological analysis, experienced a decrease in fire frequency after 1850 [or the "end of the Little Ice Age," as they describe it] (Bergeron and Archambault, 1993; Larsen, 1996) and a further decrease after 1940 (Bergeron *et al*., 2001, 2004a,b, 2006)."

Similar findings were reported by Lauzon *et al*. (2007) while investigating the fire history of a 6,480-km^2 area located in the Baie-Des-Chaleurs region of Gaspesie at the southeastern edge of Quebec "using Quebec Ministry of Natural Resource archival data and aerial photographs combined with dendrochronological data." Coincident with the 150-year warming that led to the demise of the Little Ice Age and the establishment of the Current Warm Period, the three researchers reported there was "an increase in the fire cycle from the pre-1850 period (89 years) to the post-1850 period (176 years)," and "both maximum and mean values of the Fire Weather Index decreased statistically between 1920 and 2003." During the latter period, they observed, "extreme values dropped from the very high to high categories, while mean values changed from moderate to low categories." In contrast with model projections, and in this particular part of the world, twentieth century global warming has led to a significant decrease in the frequency of forest fires, as weather conditions conducive to their occurrence have become less prevalent and extreme.

Girardin *et al*. (2006) hypothesized "human-induced climate change could lead to an increase in forest fire activity in Ontario, owing to the increased frequency and severity of drought years, increased climatic variability and incidence of extreme climatic events, and increased spring and fall temperatures." They noted "climate change therefore could cause longer fire seasons (Wotton and Flannigan, 1993), with greater fire activity and greater incidence of extreme fire activity years (Colombo *et al*., 1998; Parker *et al*., 2000)." To provide a more rigorous test of the hypothesis than could be provided by the historical observational record, they determined it should be placed in a much longer context. Girardin *et al*. inferred past area burned in Ontario for the period AD 1781–1982 by regressing tree-ring chronologies against actual area burned data and developing transfer functions they used "to estimate annual area burned at times during which there were no instrumental data."

The three researchers reported "while in recent decades area burned has increased, it remained below the level recorded prior to 1850 and particularly below levels recorded in the 1910s and 1920s." The researchers further noted "the most recent increase in area burned in the province of Ontario was preceded by the period of lowest fire activity ever estimated for the past 200 years (1940s–1960s)," despite the fact "humans during the past decades have been an important source of fire ignition." Consequently, although according to theory "one should expect greater area burned in a changing climate," their findings revealed just the opposite.

The robust nature of the Canadian scientists' findings is substantiated by "numerous studies of forest stand age distributions [an independent way of assessing the matter] across the Canadian boreal forest [a larger area than Ontario alone] [that] report lower fire activity since circa 1850 (Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Bergeron *et al*., 2001, 2004a, 2004b; Tardif, 2004)."

Beaty and Taylor (2009) developed a 14,000-year record of fire frequency based on high-resolution charcoal analysis of a 5.5-m-long sediment core extracted from Lily Pond (39°3'26"N, 120°7'21"W) in the General Creek Watershed on the west shore of Lake Tahoe in the northern Sierra Nevada in California (USA), as well as a 20-cm-long surface core that "preserved the sediment-water interface."

They found "fire episode frequency was low during the Lateglacial period but increased through the middle Holocene to a maximum frequency around 6500 cal. yr BP," which "corresponded with the Holocene temperature maximum (7000–4000 cal. yr BP)." Thereafter, as the temperature gradually declined, so too did fire frequency, except for a multicentury aberration they described as "a similar peak in fire episode frequency [that] occurred between c. 1000 and 600 cal. yr BP during the 'Medieval Warm Period,'" which they indicated was followed by an interval "between c. 500 and 200 cal. yr BP with few charcoal peaks [that] corresponded with the so-called 'Little Ice Age.'" Arriving at the present, they find the "current fire episode frequency on the west shore of Lake Tahoe is at one of its lowest points in at least the last 14,000 years."

A contrary example, where warming does appear to have enhanced fire occurrence, is provided by Pierce *et al*. (2004), who dated fire-related sediment deposits in alluvial fans in central Idaho, USA, in a research program designed to reconstruct Holocene fire history in xeric ponderosa pine forests and to look for links to past climate change. This endeavor focused on tributary alluvial fans of the South Fork Payette (SFP) River area, where fans receive sediment from small but steep basins in weathered batholith granitic rocks conducive to post-fire erosion. Altogether, they obtained 133 AMS ^{14}C-derived dates from 33 stratigraphic sites in 32 alluvial fans. In addition, they compared their findings with those of Meyer *et al*. (1995), who had earlier reconstructed a similar fire history for nearby Yellowstone National Park in Wyoming, USA.

Pierce *et al*.'s work revealed "intervals of stand-replacing fires and large debris-flow events are largely coincident in SFP ponderosa pine forests and Yellowstone, most notably during the 'Medieval Climatic Anomaly' (MCA), ~1,050-650 cal. yr BP." They also noted "in the western USA, the MCA included widespread, severe miltidecadal droughts (Stine, 1998; Woodhouse and Overpeck, 1998), with increased fire activity across diverse northwestern conifer forests (Meyer *et al*., 1995; Rollins *et al*., 2002)."

Following the Medieval Warm Period and its frequent large-event fires was the Little Ice Age, when, as Pierce *et al*. described it, "colder conditions maintained high canopy moisture, inhibiting stand-replacing fires in both Yellowstone lodgepole pine forests and SFP ponderosa pine forests (Meyer *et al*., 1995; Rollins *et al*., 2002; Whitlock *et al*., 2003)." Subsequently, they reported, "over the twentieth century, fire size and severity have increased in most ponderosa pine forests," which they suggest may be largely due to "the rapidity and magnitude of twentieth-century global climate change."

Westerling *et al*. (2006), who compiled a comprehensive database of large wildfires in western United States forests since 1970 and compared it to hydroclimatic and land-surface data, reached similar conclusions. Their findings are succinctly summarized by Running (2006) in an accompanying Perspective, where he wrote "since 1986, longer warmer summers have resulted in a fourfold increase of major wildfires and a sixfold increase in the area of forest burned, compared to the period from 1970 to 1986," noting also "the length of the active wildfire season in the western United States has increased by 78 days, and that the average burn duration of large fires has increased from 7.5 to 37.1 days." In addition, he states, "four critical factors—earlier snowmelt [by one to four weeks], higher summer temperatures [by about 0.9°C], longer fire season, and expanded vulnerable area of high-elevation forests—are combining to produce the observed increase in wildfire activity."

Schoennagel *et al*. (2007) investigated "climatic mechanisms influencing subalpine forest fire occurrence in western Colorado, which provide a key to the intuitive link between drought and large, high-severity fires that are keystone disturbance processes in many high-elevation forests in the western United States," focusing on three major climatic oscillations: the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO).

They found "fires occurred during short-term periods of significant drought and extreme cool (negative) phases of ENSO and [the Pacific Decadal Oscillation (PDO)] and during positive departures from [the mean Atlantic Multidecadal Oscillation (AMO)] index," while "at longer time scales, fires exhibited 20-year periods of synchrony with the cool phase of the PDO, and 80-year periods of synchrony with extreme warm (positive) phases of the AMO." In addition, they note "years of combined positive AMO and negative ENSO and PDO phases represent 'triple whammies' that significantly increased the occurrence of drought-induced fires." On the other hand, they observed "drought and wildfire are associated with warm phases of ENSO and PDO in the Pacific Northwest and northern Rockies while the opposite occurs in the Southwest and southern Rockies," citing the findings of Westerling and Swetnam (2003), McCabe *et al*. (2004), and Schoennagel *et al*. (2005). Schoennagel *et al*. thus concluded "there remains considerable uncertainty regarding the effects of CO_2-induced warming at regional scales." Nevertheless, they reported, "there is mounting evidence that the recent shift to the positive phase of the AMO will promote higher fire frequencies" in the region of their study, high-elevation western U.S. forests, though such a consequence should not necessarily be viewed as a response to CO_2-induced global warming.

Brunelle *et al*. (2010) collected sediments during the summers of 2004 and 2005 from a drainage basin located in southeastern Arizona (USA) and north-eastern Sonora (Mexico), from which samples were taken "for charcoal analysis to reconstruct fire history" as well as pollen data to infer something about climate.

According to the U.S. and Mexican researchers, "preliminary pollen data show taxa that reflect winter-dominated precipitation [which implies summer drought] correspond to times of greater fire activity," and the results from the fire reconstruction "show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly." During this latter period, from approximately AD 900 to 1260, "background charcoal reaches the highest level of the entire record and fire peaks are frequent," and "the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al*., 2004)."

Brunelle *et al*. speculated if the region of their study warms in the future, "the role of fire in the desert grasslands is likely to change," such that "warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires, similar to >5000 cal yr BP."

Pitkanen *et al*. (2003) constructed a Holocene fire history of dry heath forests in eastern Finland on the basis of charcoal layer data obtained from two small mire basins and fire scars on living and dead pine trees. This work revealed a "decrease in fires during climatic warming in the Atlantic chronozone (about 9000–6000 cal. yr. BP)," prompting them to conclude "the very low fire frequency during the Atlantic chronozone despite climatic warming with higher summer temperatures, is contrary to assumptions about possible implications of the present climatic warming due to greenhouse gasses." Thereafter, the researchers observed an increase in fire frequency at the transition between the Atlantic and Subboreal chronozones around 6000 cal. yr. BP, noting "the climatic change that triggered the increase in fire frequency was cooling and a shift to a more continental climate." In addition, they reported the data of Bergeron and Archambault (1993) and Carcaillet *et al*. (2001) from Canada suggest much the same thing; i.e., a decrease in boreal forest fires during periods of greater warmth. Consequently, "as regards the concern that fire frequency will increase in [the] near future owing to global warming," the researchers say their data "suggest that fires from 'natural' causes (lightning) are not likely to increase significantly in eastern Finland and in geographically and climatically related areas."

Wallenius *et al*. (2011) observed "the effect of ongoing climate change on forest fires is a hotly debated topic," with many "experts" arguing "the climatic warming in the 20th and 21st century has resulted and will result in an increase in forest fires." Against this backdrop Wallenius *et al*. set out to "add information about forest fire history of the as-yet poorly studied *Larix*-dominated forests of central Siberia by means of high-precision dendro-chronological dating of past fires."

Studying the northern part of the Irkutsk district of central Siberia (centered at approximately 60.75°N, 107.75°E) in areas "untouched by modern forestry and agriculture," where "population density is low, with less than 0.1 inhabitant per square kilometer," the group of Finnish, Panamanian, and Russian researchers determined "in the 18th century, on average, 1.9% of the forests burned annually, but in the 20th century, this figure was only 0.6%," and "the fire cycles for these periods were 52 and 164 years, respectively." In addition, they reported "a further analysis of the period before the enhanced fire control program in the 1950s revealed a significant lengthening in the fire cycle between the periods 1650–1799 and 1800–1949, from 61 to 152 years, respectively." They noted "a similar phenomenon has been observed in Fennoscandia, southern Canada and the western United States, where the annually burned proportions have decreased since the 19th century (Niklasson and Granstrom, 2000; Weir *et al*., 2000; Heyerdahl *et al*., 2001; Bergeron *et al*., 2004b)." They also found "in these regions, the decrease has been mostly much steeper, and the current fire cycles are several hundreds or thousands of years."

Turner *et al*. (2008) analyzed micro-charcoal, pollen, and stable oxygen isotope ($\delta^{18}O$) data obtained from sediment cores extracted from two crater lake basins in central Turkey, from which they reconstructed synchronized fire, vegetation, and climate histories that extend back in time more than 15,000 years. The authors determined "climatically-induced variation in biomass availability was the main factor controlling the timing of regional fire activity during the Last Glacial-Interglacial climatic transition, and again during Mid-Holocene times, with fire frequency and magnitude increasing during wetter climatic phases." In addition, they reported spectral analysis of the Holocene part of the record "indicates significant cyclicity with a periodicity of ~1500 years that may be linked with large-scale climate forcing."

McAneney *et al*. (2009) assembled a much different database for evaluating the global warming/fire relationship as it pertains to Australia. The primary source of information for their study was the "Risk Frontiers' disaster database of historic building losses—PerilAUS—which provides a reasonably faithful testimony of national building losses from 1900," with additional information provided by the Insurance Council of Australia's database of significant insured losses.

The three researchers noted "the annual aggregate numbers of buildings destroyed by bushfire since 1926 ... is 84," but "most historical losses have taken place in a few extreme fires." Nevertheless, they observed "the most salient result is that the annual probability of building destruction has remained almost constant over the last century," even in the face of "large demographic and social changes as well as improvements in fire fighting technique and resources."

The researchers restated this finding many times: (1) "the historical evidence shows no obvious trend," (2) "the likelihood of losing homes to bushfire has remained remarkably stable over the last century with some building destruction expected in around 55% of years," (3) "this same stability is also exhibited for the bigger events with an annual probability of losing more than 25 or 100 homes in a single week remaining around 40% and 20% respectively," and (4) "the statistics on home destruction have remained obstinately invariant over time." In addition, McAneney *et al*. noted "Australia's population has increased from around 4 to 20 million over the last century," and therefore we might logically have expected "the likelihood of bushfire losses to have increased with population or at least with the population living immediately adjacent to bushlands." McAneney *et al*. concluded, "despite predictions of an increasing likelihood of conditions favoring bushfires under global climate change, we suspect that building losses due to bushfires are unlikely to alter materially in the near future."

Although specific areas of the planet experienced both significant increases and decreases in land area burned over the last two or three decades of the twentieth century, as illustrated in the materials reviewed above, what is the case for the world as a whole; i.e., what is the net result of the often opposite wildfire responses to warming that are typical of different parts of the planet?

Girardin *et al*. (2009) investigated "changes in wildfire risk over the 1901–2002 period with an analysis of broad-scale patterns of drought variability on forested eco-regions of the North American and Eurasian continents." The seven scientists reported "despite warming since about 1850 and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so (e.g. Masters, 1990; Johnson and Larsen, 1991; Larsen, 1997; Lehtonen and Kolstrom, 2000; Bergeron *et al*., 2001, 2004a,b; Mouillot and Field, 2005)." They found "this holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia."

With respect to this long-term "diminishing fire activity," Girardin *et al*. observed "the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction." That role would appear to be one of reducing fire activity. To emphasize that point and provide still more evidence for it, the authors noted, "the fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control."

Riano *et al*. (2007) conducted "an analysis of the spatial and temporal patterns of global burned area with the Daily Tile US National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer Pathfinder 8 km Land dataset between 1981 and 2000." As demonstrated previously, for several areas of the world this investigation revealed there were indeed significant upward trends in land area burned. Some parts of Eurasia and western North America, for example, had annual upward trends as high as 24.2 pixels per year, where a pixel represents an area of 64 km^2. These increases in burned area, however, were offset by equivalent decreases in burned area in tropical Southeast Asia and Central America. Consequently, observed Riano *et al*., "there was no significant global annual upward or downward trend in burned area." They also noted "there was also no significant upward or downward global trend in the burned area for any individual month." In addition, they found "latitude was not determinative, as divergent fire patterns were encountered for various land cover areas at the same latitude."

In one additional paper providing a global view of the subject, but over a longer time scale, Marlon *et al*. (2008) observed "large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes," and "climate-change projections indicate that we will be moving quickly out of the range of the natural variability of the past few centuries." In an effort to see what the global wildfire "range of natural variability" actually has been, Marlon *et al*. used "sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning [over] the past two millennia."

The international team of researchers reported "global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870," after which it "declined abruptly." In terms of attribution, they said the initial long-term decline in global biomass burning was due to "a long-term global cooling trend," while they suggested the rise in fires that followed was "linked to increasing human influences." With respect to the final decline in fires that took place after 1870, however, they noted it occurred "despite increasing air temperatures and population." As for what may have overpowered the tendency for increased global wildfires that would "normally" have been expected to result from the global warming of the Little Ice Age-to-Current Warm Period transition, the nine scientists attributed "reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management."

Evidence from prior centuries suggests global warming may indeed have had a tendency to promote wildfires on a global basis (since global cooling had a tendency to reduce them), but technological developments during the industrial age appear to have overpowered this natural tendency. It appears humans have become a dominant factor leading to a decrease in global wildfires over the past century and a half. Although one can readily identify specific parts of the planet that have experienced significant increases or decreases in land area burned over the past several decades, for the globe as a whole there has been no relationship between rising temperatures and total area burned over this latter period.

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7.4 Drought

One of the many assumed dangers of global warming is the predicted propensity for rising temperatures to produce more frequent, more severe, and longer-lasting droughts almost everywhere on Earth. In its most recent assessment report, the IPCC presents the following statements regarding the attribution of historic drought to human-induced global warming:

> While the [*Fourth Assessment Report*] concluded that it is more likely than not that anthropogenic influence has contributed to an increase in the droughts observed in the second half of the 20th century, an updated assessment of the observational evidence indicates that the AR4 conclusions regarding global increasing trends in hydrological droughts since the 1970s are no longer supported. Owing to the low confidence in observed large-scale trends in dryness combined with difficulties in distinguishing decadal-scale variability in drought from long term climate change we now conclude there is low confidence in the attribution of changes in drought over global land since the mid-20th century to human influence (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 31).
>
> The current assessment does not support the [*Fourth Assessment Report*] conclusions regarding global increasing trends in droughts but rather concludes that there is not enough evidence at present to suggest high confidence in observed trends in dryness. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 61).

Although the IPCC has revised downward its confidence in the attribution of historical drought to rising CO_2 emissions, it is doing so because the IPCC claims it has little confidence in the observed data trends and not enough data exist to validate its model-based theory on drought.

Section 7.4 presents a comprehensive analysis of the observational data on drought, demonstrating there exists a large body of peer-reviewed science that invalidates the model-based claims of global warming causing more drought.

7.4.1 Africa

Data presented in numerous peer-reviewed studies do not support the model-based claim CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Africa.

In “A multimodel study of the twentieth-century simulations of Sahel drought from the 1970s to 1990s," Lau *et al*. (2006) explored "the roles of sea surface temperature coupling and land surface processes in producing the Sahel drought in CGCMs [coupled general circulation models] that participated in the twentieth-century coupled climate simulations of the Intergovernmental Panel on Climate Change [IPCC] Assessment Report 4." The scientists examined 19 CGCMs, each of which was "driven by combinations of realistic prescribed external forcing, including anthropogenic increase in greenhouse gases and sulfate aerosols, long-term variation in solar radiation, and volcanic eruptions." The work revealed "only eight models produce a reasonable Sahel drought signal, seven models produce excessive rainfall over [the] Sahel during the observed drought period, and four models show no significant deviation from normal." In addition, the scientists reported "even the model with the highest skill for the Sahel drought could only simulate the increasing trend of severe drought events but not the magnitude, nor the beginning time and duration of the events."

Since all 19 CGCMs used in preparing the IPCC's *Fourth Assessment Report* were unable to adequately simulate the basic characteristics of what Lau *et al*. call one of the past century's "most pronounced signals of climate change," this failure of what they call an "ideal test" for evaluating the models' abilities to accurately simulate "long-term drought" and "coupled atmosphere-ocean-land processes and their interactions" suggests extreme caution in relying on any of the models' output as a guide to the future. Even though the models were "driven by combinations of realistic prescribed external forcing," they could not properly simulate even the recent past.

Shifting attention to instrumental and proxy drought records, Nicholson (2001) reported in a review of information pertaining to the past two centuries there has been "a long-term reduction in rainfall in the semi-arid regions of West Africa" that has been "on the order of 20 to 40% in parts of the Sahel." Describing the phenomenon as "three decades of protracted aridity," she observed "nearly all of Africa has been affected ... particularly since the 1980s." Nevertheless, Nicholson reported "rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented" and "a similar dry episode prevailed during most of the first half of the 19th century," when much of the planet was still experiencing Little Ice Age conditions.

Therrell *et al*. (2006) developed "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This revealed "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995)," and "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They reported, for example, the year 1860 (the most droughty year of the entire period) was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, Therrel *et al*. reported "a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era." Consequently, for a large part of central southern Africa, the supposedly unprecedented global warming of the twentieth century did not result in an intensification of either extreme dry or wet periods. If anything, just the opposite appears to have occurred.

Esper *et al.* (2007) reported similar findings, noting "analysis of the PDSI [Palmer Drought Severity Index], a standardized measure of surface moisture conditions, revealed distinct 20th century aridity changes in vulnerable NW Africa, including a sharp downward trend towards drier conditions in the 1980s (Luterbacher *et al*., 2006)," but "a high-resolution long-term reconstruction that could place current conditions in the context of the past millennium is missing for N Africa," which the authors set out to develop. Esper *et al*. "re-use *Cedrus atlantica* tree-ring data generated in the 1980s (Glueck and Stockton, 2001) and combine these measurements with a major update collected in 2002," which "allows analysis of tree growth and instrumental data during the current drought episode in comparison to PDSI estimates back to AD 1049."

The six scientists reported "PDSI values were above average for most of the 1450–1980 period, which let recent drought appear exceptional." However, they found the long-term results they obtained indicated the "pluvial episode of the past millennium was preceded by generally drier conditions back to 1049," leading them to state the late twentieth century drought "appears more typical when associated with conditions before 1400." In addition, they concluded, the "ultimate drivers" for the medieval hydroclimate pattern that led to the earlier drought conditions in Morocco "seemed to be high solar irradiance and low volcanic forcings (Emile-Geay *et al*., 2007)."

Verschuren *et al*. (2000) developed a decadal-scale history of rainfall and drought in equatorial east Africa for the past thousand years based on level and salinity fluctuations of a small crater-lake in Kenya, using data derived from diatom and midge assemblages retrieved from the lake's sediments. They found the Little Ice Age was generally wetter than the Modern Warm Period, but they identified three intervals of prolonged dryness within the Little Ice Age (1390–1420, 1560–1625, and 1760–1840). They note these "episodes of persistent aridity" were "more severe than any recorded drought of the twentieth century."

Holmes *et al.* (1997) probed 1,500 years into the past, reporting the African Sahel since the late 1960s has experienced "one of the most persistent droughts recorded by the entire global meteorological record."In a high-resolution study of a sediment sequence extracted from an oasis in the Manga Grasslands of northeast Nigeria, they determined "the present drought is not unique and that drought has recurred on a centennial to interdecadal timescale during the last 1500 years."

Russell *et al.* (2007) added another 500 years to the analysis, conducting lithostratigraphic analyses of sediment cores obtained from two crater lake basins in Western Uganda, Africa—Lake Kitagata (0°03'S, 29°58'E) and Lake Kibengo (0°04.9'S, 30°10.7'E)—spanning the past two millennia. Among other things, Russell *et al*. reported "variations in sedimentation and salt mineralogy of hypersaline Lake Kitagata, and a succession of fine-grained lake sediments and peat in the freshwater Lake Kibengo, suggest century-scale droughts centered on AD ~0 [and] ~1100."

Discussing what they called the "broader climatic implications" of their findings, the three researchers reported "based on comparison of proxy water-balance records from Lakes Edward (Russell *et al*., 2003; Russell and Johnson, 2005), Naivasha (Verschuren *et al*., 2000), Turkana (Halfman *et al*., 1994), and Tanganyika (Alin and Cohen, 2003), Russell *et al*. (2003) argued that drought around 2000 years ago (AD ~0) affected 'much, if not all, of equatorial Africa.'" Similarly, they observed, "Verschuren (2004) argued that drought centered on AD 1150 affected much of the region, a hypothesis supported by Russell and Johnson (2005)." Consequently, and in light of their similar, newer results, the three scientists concluded "droughts at AD ~0 and ~1150"—which roughly mark the midpoints of the Roman and Medieval Warm Periods, respectively—"do appear to have affected much of equatorial Africa."

Russell and Johnson (2005) derived a detailed precipitation history from sediment cores retrieved from Lake Edward, the smallest of the great rift lakes of East Africa, located on the border that separates Uganda and the Democratic Republic of the Congo. They discovered from the start of the record almost 5,500 years ago until approximately 1,800 years ago, there was a long-term trend toward progressively more arid conditions, after which there followed a "slight trend" toward wetter conditions that has persisted to the present. Superimposed on these long-term trends were major droughts of "at least century-scale duration," centered at approximately 850, 1,500, 2,000, and 4,100 years ago.

The studies cited here make clear the need for long-term (millennial-scale) records of climatic and meteorological phenomena in order to determine how exceptional twentieth century changes in their characteristics might be, which can help determine whether there is compelling reason to attribute such changes to historical increases in the atmospheric concentrations of greenhouse gases. For Africa, real-world evidence suggests the global warming of the past century or so has not led to a greater frequency or severity of drought in that part of the world. Even the continent's worst drought in recorded meteorological history does not seem to have been any worse (in fact, it was much milder) than droughts that occurred in the historic past. There is little reason to expect global warming to lead to more frequent or severe droughts in Africa.

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Verschuren, D., Laird, K.R., and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* **403**: 410–414.

7.4.2 Asia

As noted in the introduction to this Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Asia.

Using a multimodel approach developed previously (Wang *et al*., 2009), Wang *et al*. (2011) employed four physically based land surface hydrology models driven by an observation-based three-hourly meteorological dataset to simulate soil moisture over China for the period 1950–2006, deriving monthly values of total column soil moisture from which they calculated agricultural drought severities and durations. The authors reported "for drought areas greater than 150,000 km^2 and durations longer than three months, a total of 76 droughts were identified," and "regions with downward trends were larger than those with upward trends (37% versus 26% of the land area)," implying "over the period of analysis, the country has become slightly drier in terms of soil moisture."

Wang *et al*.'s findings are not proof of a CO_2-induced temperature link, nor do they imply an increase in future drought. Any suggestion of a link between drought and global warming is unique to the Wang *et al.* study, perhaps because their drought calculations are derived from models simulating soil moisture as opposed to measuring it. With respect to the future, Wang *et al*. report "climate models project that a warmer and moister atmosphere in the future will actually lead to an enhancement of the circulation strength and precipitation of the summer monsoon over most of China (e.g., Sun and Ding, 2010) that will offset enhanced drying due to increased atmospheric evaporative demand in a warmer world (Sheffield and Wood, 2008)."

Tao and Zhang (2011) provide some support for this statement. Using the Lund-Potsdam-Jena Dynamic Global Vegetation Model, they concluded the net effect of physiological and structural vegetation responses to expected increases in the air's CO_2 content will lead to "a decrease in mean evapotranspiration, as well as an increase in mean soil moisture and runoff across China's terrestrial ecosystem in the 21st century," which should act to lessen, or even offset, the "slightly drier" soil moisture conditions modeled by Wang *et al*.

In other studies examining drought trends in Asia—and China in particular—Paulsen *et al*. (2003) employed high-resolution stalagmite records of $\delta^{13}C$ and $\delta^{18}O$ from Buddha Cave "to infer changes in climate in central China for the last 1270 years in terms of warmer, colder, wetter and drier conditions." Among the climatic episodes evident in their data were "those corresponding to the Medieval Warm Period, Little Ice Age and 20th-century warming, lending support to the global extent of these events." Their record began in the depths of the Dark Ages Cold Period, which ended approximately AD 965 with the commencement of the Medieval Warm Period, and continued to approximately AD 1475, whereupon the Little Ice Age set in and held sway until about AD 1825, after which the warming responsible for the Modern Warm Period began.

With respect to hydrologic balance, the last part of the Dark Ages Cold Period was characterized as wet. It was followed by a dry, a wet, and another dry interval in the Medieval Warm Period, which was followed by a wet and a dry interval in the Little Ice Age, and finally a mostly wet but highly moisture-variable Modern Warm Period. Paulsen *et al*.'s data also revealed other cycles superimposed on the major millennial-scale cycle of temperature and the centennial-scale cycle of moisture, and they attributed most of these higher-frequency cycles to solar phenomena. The authors concluded the summer monsoon over eastern China, which brings the region much of its precipitation, may "be related to solar irradiance."

The authors' data indicated Earth's climate is determined by a conglomerate of cycles within cycles, all of which are essentially independent of the air's CO_2 concentration. The data also demonstrated the multicentury warm and cold periods of the planet's millennial-scale oscillation of temperature may have both wetter and drier periods embedded within them. Consequently, warmth alone is not a sufficient condition for the occurrence of the dryness associated with drought.

Jiang *et al*. (2005) analyzed historical documents to produce a time series of flood and drought occurrences in eastern China's Yangtze Delta since AD 1000. They found alternating wet and dry episodes throughout this lengthy period, and the data demonstrated droughts and floods usually occurred in the spring and autumn seasons of the same year, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850), as opposed to the preceding Medieval Warm Period and the following Current Warm Period.

Zhang *et al*. (2007) developed for China's Yangtze Delta region flood and drought histories of the past thousand years based on "local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," after which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." They described this as "a powerful way to characterize the frequency, the intensity, the time position, and the duration of variations in a climate data series." They also compared their results with two 1,000-year temperature histories of the Tibetan Plateau, encompassing northeastern Tibet and southern Tibet.

Zhang *et al*. reported during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they reported during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/ drought series in the Yangtze Delta region."

Zhang *et al*. (2009) utilized the decadal locust (*Locusta migratoria manilensis*) abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al*. (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al*. (2002) for the AD 950s–1950s to perform a wavelet analysis "to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China." The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events.

The six scientists observed "global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China," noting these findings "challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects." They reported their results are an example of "benign effects of global warming on the regional risk of natural disasters."

Davi *et al*. (2006) employed absolutely dated tree-ring-width chronologies from five sampling sites in the west-central region of Mongolia—all "in or near the Selenge River basin, the largest river in Mongolia"—to develop a reconstruction of stream-flow that extended from 1637 to 1997. Of the 10 driest five-year periods of the 360-year record, they found only one occurred during the twentieth century (and that just barely: 1901–1905, sixth driest of the 10 extreme periods), and of the 10 wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the 10 extreme periods, respectively). Consequently, "there is much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," such that over the course of the twentieth century, which the IPCC describes as having experienced a warming unprecedented over the past one to two millennia, extremes of both dryness and wetness were less frequent and less severe.

Kalugin *et al*. (2005) utilized sediment cores from Lake Teletskoye in the Altai Mountains of Southern Siberia to produce a multiproxy climate record spanning the past 800 years. This record revealed the regional climate was relatively warm with high terrestrial productivity from AD 1210 to 1380. Thereafter, however, temperatures cooled and productivity dropped, reaching a broad minimum between 1660 and 1700. This interval "corresponds to the age range of the well-known Maunder Minimum (1645–1715)" and is "in agreement with the timing of the Little Ice Age in Europe (1560–1850)."

With respect to moisture and precipitation, Kalugin *et al*. reported the period between 1210 and 1480 was more humid than today, and the period between 1480 and 1840 was more arid. In addition, they reported three episodes of multiyear drought (1580–1600, 1665–1690, and 1785–1810). These findings are in agreement with other historical data and tree-ring records from the Mongolia-Altai region (Butvilovskii, 1993; Jacoby *et al*., 1996; Panyushkina *et al*., 2000). All of the major multiyear droughts detected in this study occurred during the cool phase of the 800-year record.

Kim *et al*. (2009) developed a 200-year history of precipitation measured at Seoul, Korea (1807 to 2006), along with the results of a number of "progressive methods for assessing drought severity from diverse points of view," including the Effective Drought Index (EDI) developed by Byun and Wilhite (1999), which Kim *et al*. describe as "an intensive measure that considers daily water accumulation with a weighting function for time passage"; a Corrected EDI that "considers the rapid runoff of water resources after heavy rainfall" (CEDI); an Accumulated EDI that "considers the drought severity and duration of individual drought events" (AEDI); and a year-accumulated negative EDI "representing annual drought severity" (YAEDI).

The researchers' precipitation history and two of their drought severity histories are presented, in that order, in Figures 7.4.2.1 and 7.4.2.2.

The figures clearly show the only major multiyear deviation from long-term normalcy is the decadal-scale decrease in precipitation and ensuing drought, each of which achieved their most extreme values (low in the case of precipitation, high in the case of drought) in the vicinity of AD 1900, well before the twentieth century rise in atmospheric CO_2 and global temperatures. The significant post-Little Ice Age warming of the planet thus had essentially no effect on the long-term histories of either precipitation or drought at Seoul, Korea, adding to the growing body of such findings throughout Asia.

Touchan *et al*. (2003) developed two reconstructions of spring precipitation for south-western Turkey from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia,* and *Pinus nigra*, and the other one (1339–1998) based on three chronologies of *Juniperus excelsa*. The records "show clear evidence of multi-year to decadal variations in spring precipitation." Nevertheless, the researchers reported "dry periods of 1–2 years were well distributed throughout the record" and the same was largely true of wet periods. With respect to more extreme events, the period preceding the industrial revolution stood out. They note, for example, "all of the wettest 5-year periods occurred prior to 1756." The longest period of reconstructed spring drought was the four-year period 1476–1479, and the single

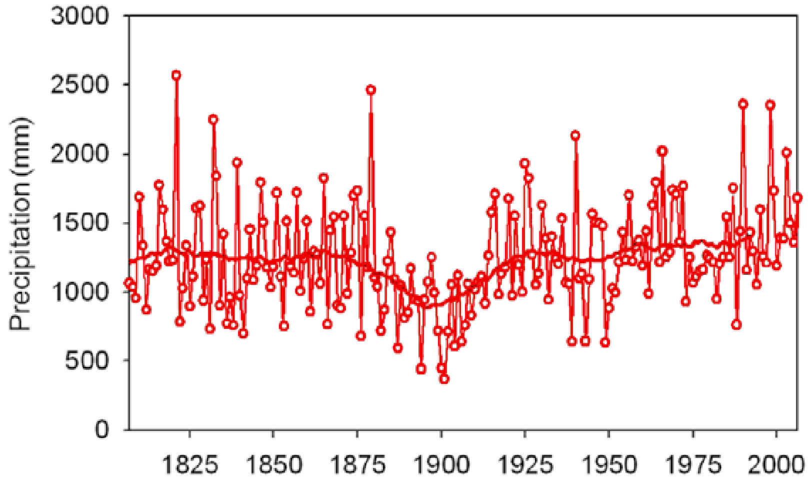

Figure 7.4.2.1. Annual precipitation history at Seoul, Korea, where the solid line represents a 30-year moving-average. Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12.

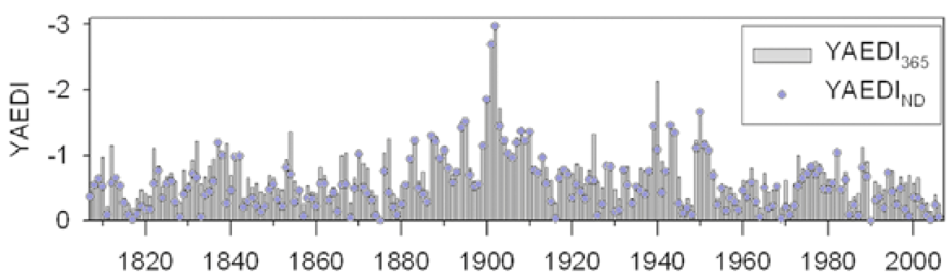

Figure 7.4.2.2. Annual "dryness" history at Seoul, Korea, represented by YAEDI365 (sum of daily negative EDI values divided by 365, represented by bars) and YAEDIND (sum of daily negative EDI values divided by total days of negative EDI, represented by open circles). Adapted from Kim, D.-W., Byun, H.-R., and Choi, K.-S. 2009. Evaluation, modification, and application of the Effective Drought Index to 200-Year drought climatology of Seoul, Korea. *Journal of Hydrology* **378**: 1–12..

driest spring was 1746.

Sinha *et al*. (2007) derived a nearly annually resolved record of Indian summer monsoon (ISM) rainfall variations for the core monsoon region of India from AD 600 to 1500 based on a ^{230}Th-dated stalagmite oxygen isotope record from Dandak Cave, located at 19°00'N, 82°00'E. The authors noted "the short instrumental record of ISM under-estimates the magnitude of monsoon rainfall variability" and "nearly every major famine in India [over the period of their study] coincided with a period of reduced monsoon rainfall as reflected in the Dandak δ^{18}O record." They found two particularly devastating famines "occurred at the beginning of the Little Ice Age during the longest duration and most severe ISM weakening of [their] reconstruction." they also observed "ISM reconstructions from Arabian Sea marine sediments (Agnihotri *et al*., 2002; Gupta *et al*., 2003; von Rad *et al*., 1999), stalagmite δ^{18}O records from Oman and Yemen (Burns *et al*., 2002; Fleitmann *et al*., 2007) and a pollen record from the western Himalaya (Phadtare and Pant, 2006) also indicate a weaker monsoon during the Little Ice Age and a relatively stronger monsoon during the Medieval Warm Period." The eight researchers noted "since the end of the Little Ice Age, ca 1850 AD, the human population in the Indian monsoon region has increased from about 200 million to over 1 billion," and "a recurrence of weaker intervals of ISM comparable to those inferred in our record would have serious implications to human health and economic sustainability in the region."

Sinha *et al*. (2011) warned the return of a severe drought to India could pose a "serious threat for the predominantly agrarian-based societies of monsoon Asia, where the lives of billions of people are tightly intertwined with the annual monsoon cycle." The eight researchers from China, Germany, and the United States reviewed the history of the monsoon, relying heavily on the work of Sinha *et al*. (2007) and Berkelhammer *et al*. (2010).

Sinha *et al*. (2011) observed "proxy reconstructions of precipitation from central India, north-central China [Zhang *et al*., 2008], and southern Vietnam [Buckley *et al*., 2010] reveal a series of monsoon droughts during the mid 14th-15th centuries that each lasted for several years to decades," and "these monsoon megadroughts have no analog during the instrumental period." They noted "emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley *et al*., 2007; Sano *et al*., 2009) and India (Borgaonkar *et al*., 2010) suggest that the mid 14th-15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the Little Ice Age" and "appear to have played a major role in shaping significant regional societal changes at that time." Among these upheavals, they made special mention of "famines and significant political reorganization within India (Dando, 1980; Pant *et al*., 1993; Maharatna, 1996), the collapse of the Yuan dynasty in China (Zhang *et al*., 2008), the Rajarata civilization in Sri Lanka (Indrapala, 1971), and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley *et al*., 2010)," noting the evidence suggests "monsoon megadroughts may have played a major contributing role in shaping these societal changes."

Cluis and Laberge (2001) analyzed streamflow records stored in the databank of the Global Runoff Data Center at the Federal Institute of Hydrology in Koblenz (Germany) to see if there were any changes in Asian river runoff of the type the IPCC predicted would lead to more frequent and more severe drought. They based their study on the streamflow histories of 78 rivers said to be "geographically distributed throughout the whole Asia-Pacific region." The mean start and end dates of these series were 1936 ± 5 years and 1988 ± 1 year, respectively, representing an approximate half-century timespan.

With respect to the rivers' annual minimum discharges, which is the measure associated with drought, the authors found 53% were unchanged over the period of the study. Where there were trends, 62% of them were upward, indicative of a growing likelihood of less frequent and less severe drought.

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7.4.3 Europe

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Europe.

Noting "the media often reflect the view that recent severe drought events are signs that the climate has in fact already changed owing to human impacts," Hisdal *et al*. (2001) performed a series of statistical analyses on more than 600 daily streamflow records from the European Water Archive to examine trends in the severity, duration, and frequency of drought over the four time periods 1962–1990, 1962–1995, 1930–1995, and 1911–1995. This work revealed "despite several reports on recent droughts in Europe, there is no clear indication that streamflow drought conditions in Europe have generally become more severe or frequent in the time periods studied." To the contrary, they found "overall, the number of negative significant trends pointing towards decreasing drought deficit volumes or fewer drought events exceeded the number of positive significant trends (increasing drought deficit volumes or more drought events)."

Linderholm and Chen (2005) derived a 500-year history of winter (September–April) precipitation from tree-ring data obtained within the Northern Boreal zone of Central Scandinavia. This chronology indicated below-average precipitation occurred during the periods 1504–1520, 1562–1625, 1648–1669, 1696–1731, 1852–1871, and 1893–1958, with the lowest values occurring at the beginning of the record and at the beginning of the seventeenth century. For this portion of the European continent, twentieth century global warming did not result in more frequent or more severe droughts.

Linderholm and Molin (2005) analyzed two independent precipitation proxies, one derived from tree-ring data and one from a farmer's diary, to produce a 250-year record of summer (June–August) precipitation in east central Sweden. They found a high degree of variability in summer precipitation on interannual to decadal time scales throughout the record, with the past century exhibiting less variability than the preceding 150 years. A persistent dry episode stood out vividly between 1806 and 1832, when the tree-ring history revealed its longest consecutive period of below-average tree growth, which was associated with a concomitant period of drought documented in the farmer's diary.

Korhonen and Kuusisto (2010) observed "annual mean temperatures in Finland increased by about 0.7°C during the 20th century," citing Jylha *et al.* (2004), while noting under such a warming regime, "both droughts and floods are expected to intensify," a claim made by the IPCC. In a study designed to explore the soundness of this contention, the authors analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland up to the year 2004, using data supplied by the Finnish Environment Institute.

They found as "winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites." They note "the magnitudes of spring high flow have not changed," but low flows "have increased at about half of the unregulated sites due to an increase in both winter and summer discharges." They reported "statistically significant overall changes have not been observed in mean annual discharge."

Here too, Earth did not behave according to the model projections, in this case regarding hydrological responses to global warming. The conflict occurred at both ends of the available moisture spectrum. At the high end, there was no change in the magnitude of flows that can lead to flooding. At the low end, there was an increase in flow magnitude, which either acts to prevent droughts or leads to less frequent and/or less severe episodes of it.

Wilson *et al*. (2005) used the regional curve standardization technique to develop a summer (March–August) precipitation chronology from living and historical ring-widths of trees in the Bavarian Forest region of southeast Germany for the period 1456–2001. This technique captured low frequency variations indicating the region was substantially drier than the long-term average during the periods 1500–1560, 1610–1730, and 1810–1870, all intervals much colder than the bulk of the twentieth century.

In the Danube River in western Europe, several researchers studied the precipitation histories of adjacent regions and suggested an anthropogenic signal was present in the latter decades of the twentieth century, attributing that period's supposedly drier conditions to that anthropogenic signal. Ducic

(2005) examined those claims by analyzing observed and reconstructed discharge rates of the river near Orsova, Serbia over the period 1731–1990. Ducic found the lowest 5-year discharge value in the preinstrumental era (1831–1835) was practically equal to the lowest 5-year discharge value in the instrumental era (1946–1950), and the driest decade of the entire 260-year period was 1831–1840. Ducic also reported the discharge rate for the last decade of the record (1981–1990), which prior researchers claimed was anthropogenically influenced, was "completely inside the limits of the whole series" and only 0.7% less than the 260-year mean. The scientist concluded "modern discharge fluctuations do not point to dominant anthropogenic influence." Ducic also concluded the detected cyclicity in the record could "point to the domination of the influence of solar activity."

van der Schrier *et al*. (2006) constructed monthly maps of the Self-Calibrating Palmer Drought Severity Index (SC-PDSI, a variant put forward by Wells *et al*. (2004) of the more common PDSI) for the period 1901–2002 for Europe (35°N–70°N, 10°W–60°E). This index "improves upon the PDSI by maintaining consistent behavior of the index over diverse climatological regions," which "makes spatial comparisons of SC-PDSI values on continental scales more meaningful."

The scientists found "over the region as a whole, the mid-1940s to early 1950s stand out as a persistent and exceptionally dry period, whereas the mid-1910s and late 1970s to early 1980s were very wet." Over the entire study period, they found trends in the continent's summer moisture availability "fail to be statistically significant, both in terms of spatial means of the drought index and in the area affected by drought." In addition, they noted "evidence for widespread and unusual drying in European regions over the last few decades [as suggested by the work of Briffa *et al*. (1994) and Dai *et al*. (2004)] is not supported by the current work," in that "values for the total percentage area subject to extreme moisture conditions in the years 1996–99 returned to normal levels at ~2% from a maximum of nearly 10% in 1990." The four researchers noted "the absence of a trend toward summer desiccation has recently also been observed in soil moisture records in the Ukraine (Robock *et al*., 2005) and supports conclusions in the current study."

Pfister *et al*. (2006) identified extremely low water stages in the Upper Rhine River Basin via hydrological measurements made since 1808 at Basel, Switzerland, while "for the period prior to 1808, rocks emerging in rivers and lakes in the case of low water were used along with narrative evidence for assessing extreme events." This work revealed "29 severe winter droughts are documented since 1540," and these events "occurred after a succession of four months with below-average precipitation" associated with "persistent anticyclones centered over Western Europe." The scientists found "severe winter droughts were relatively rare in the 20th century compared to the former period, which is due to increased winter temperature and precipitation." They noted "extended droughts in the winter half-year in Central Europe were more frequent, more persistent and more severe during the Little Ice Age than in the preceding 'Medieval Warm Period' and the subsequent 'warm 20th century' (Pfister, 2005)."

Renard *et al*. (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high- and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations with a minimum record length of 40 years. These analyses revealed "at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive." At the smaller scale of hydroclimatic regions, they also found no significant results for most regions, although "consistent changes were detected in three geographical areas."

Although small geographical areas often display trends in hydrological regimes of one extreme or the other (high- or low-flow), when scaling up to larger regions such as countries, there is typically less consistent change in extreme behavior. Renard *et al*. concluded "when considered at the global scale," the impact of climate change on hydrological regimes "is still an open question, as illustrated by the lack of a clear signal emerging from large-scale studies (Knudzewicz *et al*., 2005; Svensson *et al*., 2005)."

Buntgen *et al*. (2011) "introduce and analyze 11,873 annually resolved and absolutely dated ring-width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period," and which "allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations." The nine researchers found "a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming." Such findings, Buntgen *et al*. stated, "may question the common belief that frequency and severity of such events closely relates to climate mean states."

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7.4.4 North America

7.4.4.1 Canada

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Canada.

Gan (1998) performed several statistical tests on datasets pertaining to temperature, precipitation, spring snowmelt dates, streamflow, potential and actual evapotranspiration, and the duration, magnitude, and severity of drought throughout the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The results suggested the prairies have become somewhat warmer and drier over the past four to five decades, although there are regional exceptions to this. After weighing the pertinent facts, Gan reported "there is no solid evidence to conclude that climatic warming, if it occurred, has caused the Prairie drought to become more severe." Gan further noted "the evidence is insufficient to conclude that warmer climate will lead to more severe droughts in the Prairies."

Quiring and Papakyriakou (2005) used an agricultural drought index (Palmer's Z-index) to characterize the frequency, severity, and spatial extent of June–July moisture anomalies for 43 crop districts from the agricultural region of the Canadian prairies during 1920–1999. They found the single most severe June–July drought on the Canadian prairies occurred in 1961, and the next most severe droughts, in descending order of severity, occurred in 1988, 1936, 1929, and 1937, showing little net overall trend. The scientists did, however, report an upward trend in mean June–July moisture conditions. In addition, they noted "reconstructed July moisture conditions for the Canadian prairies demonstrate that droughts during the 18th and 19th centuries were more persistent than those of the 20th century (Sauchyn and Skinner, 2001)."

St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak in the Red River basin to reconstruct annual precipitation in southern Manitoba since AD 1409." According to the authors, "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement." The twentieth century warming appears to have induced more stable climatic conditions there, with fewer hydrologic extremes (floods and droughts) than was typical of Little Ice Age conditions. The authors concluded "climatic case studies in regional drought and flood planning based exclusively on experience during the 20th century may dramatically underestimate true worst-case scenarios." They further indicated "multidecadal fluctuations in regional hydroclimate have been remarkably coherent across the northeastern Great Plains during the last 600 years," and "individual dry years in the Red River basin were usually associated with larger scale drought across much of the North American interior," which suggests their results for the Red River basin also likely apply to the entire larger region.

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada to derive a non-vegetation-based high-resolution record of climate variability over the past 4,000 years. Throughout this record, periods of both increasing and decreasing moisture availability, as determined from grain size, were evident at decadal, centennial, and millennial time scales, as also was found by Laird *et al*. (2003) in a study of diatom assemblages in sediment cores taken from three additional Canadian lakes. Over the most recent 150 years, the grain size of the Pine Lake study generally remained above the 4,000-year average, indicative of relatively stable and less droughty conditions than the mean of the past four millennia.

Carcaillet *et al*. (2001) developed high-resolution charcoal histories from laminated sediment cores extracted from three small kettle lakes located within the mixed-boreal and coniferous-boreal forest region of eastern Canada, after which they determined whether vegetation change or climate change was the primary determinant of the fire frequency variation they observed, comparing their fire history with hydroclimatic reconstructions derived from $\delta^{18}O$ and lake-level data. Throughout the Climatic Optimum of the mid-Holocene, between about 7,000 and 3,000 years ago when it was significantly warmer than it is today, they found "fire intervals were double those in the last 2000 years," meaning fires were only half as frequent throughout the earlier warmer period as they were during the subsequent cooler era. They also determined "vegetation does not control the long-term fire regime in the boreal forest." Instead, they found "climate appears to be the main process triggering fire." In addition, they reported "dendroecological studies show that both frequency and size of fire decreased during the 20th century in both west (e.g. Van Wagner, 1978; Johnson *et al*., 1990; Larsen, 1997; Weir *et al*., 2000) and east Canadian coniferous forests (e.g. Cwynar, 1997; Foster, 1983; Bergeron, 1991; Bergeron *et al*., 2001), possibly due to a drop in drought frequency and an increase in long-term annual precipitation (Bergeron and Archambault, 1993)."

Girardin *et al*. (2004) developed a 380-year reconstruction of the Canadian Drought Code (CDC), a daily numerical rating of the average moisture content of deep soil organic layers in boreal conifer stands used to monitor forest fire danger, for the month of July based on 16 well-replicated tree-ring chronologies from the Abitibi Plains of eastern Canada just below James Bay. Cross-continuous wavelet transformation analyses of these data "indicated coherency in the 8–16 and 17–32-year per cycle oscillation bands between the CDC reconstruction and the Pacific Decadal Oscillation prior to 1850," whereas "following 1850, the coherency shifted toward the North Atlantic Oscillation."

These results led them to suggest "the end of [the] 'Little Ice Age' over the Abitibi Plains sector corresponded to a decrease in the North Pacific decadal forcing around the 1850s," and "this event could have been followed by an inhibition of the Arctic air outflow and an incursion of more humid air masses from the subtropical Atlantic climate sector," which may have helped reduce fire frequency and drought severity. They noted several other paleoclimate and ecological studies have suggested "climate in eastern Canada started to change with the end of the 'Little Ice Age' (~1850)," citing the works of Tardif and Bergeron (1997, 1999), Bergeron (1998, 2000), and Bergeron *et al*. (2001). Girardin *et al*. further noted Bergeron and Archambault (1993) and Hofgaard *et al*. (1999) have "speculated that the poleward retreat of the Arctic air mass starting at the end of the 'Little Ice Age' contributed to the incursion of moister air masses in eastern Canada."

Wolfe *et al*. (2005) conducted a multiproxy hydroecological analysis of Spruce Island Lake in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta. Their research revealed hydro-ecological conditions in that region varied substantially during the past 300 years, especially in terms of multidecadal dry and wet periods. Specifically, they found recent drying in the region was not the product of Peace River flow regulation that began in 1968, but rather the product of an extended drying period that was initiated in the early to mid-1900s. They also found the multiproxy hydroecological variables they analyzed were well-correlated with other reconstructed records of natural climate variability and hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with the earlier portion of the record actually depicting "markedly wetter and drier conditions compared to recent decades."

Zhang and Hebda (2005) conducted dendro-climatological analyses of 121 well-preserved sub-fossil logs discovered at the bottom of Heal Lake near the city of Victoria on Canada's Vancouver Island, plus 29 Douglas-fir trees growing nearby, allowing them to develop an ~4,000-year chronology exhibiting sensitivity to spring precipitation. They found "the magnitude and duration of climatic variability during the past 4000 years are not well represented by the variation in the brief modern period." As an example, they noted spring droughts represented by ring-width departures exceeding two standard deviations below the mean in at least five consecutive years occurred in the late AD 1840s and mid-1460s, as well as the mid-1860s BC, and were more severe than any drought of the twentieth century. They also found the most persistent drought occurred during the 120-year period between approximately AD 1440 and 1560. Other severe droughts of multidecadal duration occurred in the mid AD 760s–800s, the 540s–560s, the 150s–late-190s, and around 800 BC.

Wavelet analyses of the tree-ring chronology also revealed a host of natural oscillations on timescales of years to centuries, demonstrating the twentieth century was in no way unusual in this regard, as there were many times throughout the prior 4,000 years when it was both wetter and drier than it was during the last century of the past millennium.

Bonsal and Regier (2007) compared the spatial extent and severity of the 2001–2002 Canadian Prairie drought to previous droughts in this region based on data obtained from 21 reporting stations in southern Alberta, Saskatchewan, and Manitoba. They did this for the 1915–2002 period of reasonably extensive instrumental records, using two different drought indicators: the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) at several temporal scales. The two researchers determined "over the agricultural region of the Prairies, 2001 and 2002 generally ranked high in terms of spatial extent and severity of drought," and "at some stations the 2001/2002 drought was the most severe one on record." However, they stated "the SPI and PDSI as drought indicators revealed that the worst and most prolonged Prairie-wide droughts during the instrumental record (1915–2002) ... occurred in the early part of the 20th century (1915 through the 1930s)."

Laird and Cumming (2009) developed a history of changes in the level of Lake 259 (Rawson Lake, 49°40'N, 93°44'W) within the Experimental Lakes Area of northwestern Ontario, Canada, based on a suite of near-shore gravity cores they analyzed for diatom species identity and concentration as well as organic matter content. They found "a distinct decline in lake level of ~2.5 to 3.0 m from ~800 to 1130 AD." This interval "corresponds to an epic drought recorded in many regions of North America from ~800 to 1400 AD," which "is often referred to as the

Medieval Climatic Anomaly or the Medieval Warm Period, and encompasses 'The Great Drought' of the thirteenth century (Woodhouse and Overpeck, 1998; Woodhouse, 2004; Herweijer *et al*. 2007)."

The authors also noted the Canadian prairies are currently "experiencing reductions in surface-water availability due to climate warming and human withdrawals (Schindler and Donahue, 2006)," and "many regions in the western U.S. have experienced water supply deficits in reservoir storage with the recent multi-year drought (Cook *et al*., 2007)." They reported "these severe multi-year drought conditions pale in comparison to the many widespread megadroughts that persisted for decades and sometimes centuries in many parts of North America over the last millennium (Woodhouse, 2004)."

Wolfe *et al*. (2011) noted the level of Canada's Lake Athabasca—North America's ninth-largest lake, located in the northwest corner of Saskatchewan and the northeast corner of Alberta between 58° and 60° N—"is a sensitive monitor of climate-driven changes in streamflow from alpine catchments draining the eastern slopes of the Rocky Mountains (Wolfe *et al*., 2008; Johnston *et al*., 2010; Sinnatamby *et al*., 2010)" and "paleoenvironmental data indicate that the last millennium was punctuated by multi-decadal episodes of both higher and lower Lake Athabasca levels relative to the 20th century mean, which corresponded with fluctuations in the amount and timing of runoff from glaciers and snowpacks (Wolfe *et al*., 2008)." In addition, they reported "the highest levels of the last 1000 years occurred c. 1600–1900 CE [=AD] during the Little Ice Age (LIA), in company with maximum late-Holocene expansion of glaciers in the Canadian Rockies," and at the other end of the spectrum they reported the "lowest levels existed at c. 970–1080 CE at a time of low glacier volume," near the midpoint of the global Medieval Warm Period.

In their newest study of the subject, the four Canadian researchers expanded the timespan of the lake-level history to the past 5,200 years, based on new analyses of sediment cores they collected in July 2004 from North Pond (a lagoon on Bustard Island located at the western end of Lake Athabasca). They discovered "modern society in western Canada developed during a rare interval of relatively abundant freshwater supply—now a rapidly diminishing by-product of the LIA glacier expansion, which is in agreement with late 20th century decline in Athabasca River discharge identified in hydrometric records (Burn *et al*., 2004; Schindler and Donahue, 2006)" (see Figure 7.4.4.1.1). Their data suggested "the transition from water abundance to scarcity can occur within a human lifespan," which, as they caution, "is a very short amount of time for societies to adapt."

The data depicted in Figure 7.4.4.1.1 also suggest the peak warmth of the Medieval Warm Period—which was unrelated to any change in the atmosphere's CO_2 content—was likely significantly greater than the peak warmth to date during the Current Warm Period. The rapidly declining water level during the last couple of decades—when Earth's temperature was near its modern peak but exhibited very little trend—suggests lake level could continue its rapid downward course if planetary temperatures merely maintain their current values. Therefore, Wolfe *et al*. conclude, "as consumption of water from rivers draining the central Rocky Mountain region is on an increasing trend, we must now prepare to deal with continental-scale water-supply reductions well beyond the magnitude and duration of societal memory."

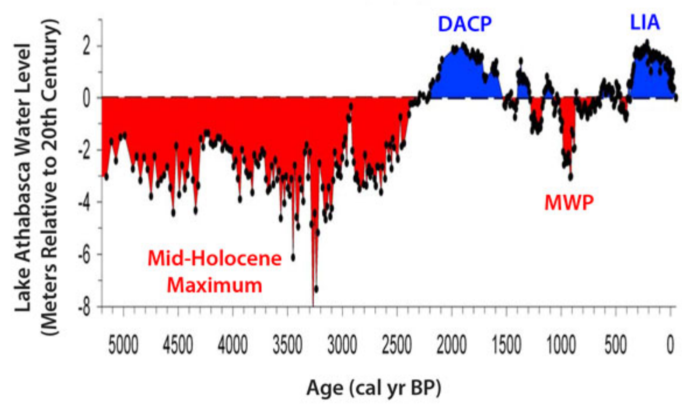

Figure 7.4.4.1.1. The Reconstructed water level history of Lake Athabasca. Adapted from Wolfe, B.B., Edwards, T.W.D., Hall, R.I., and Johnston, J.W. 2011. A 5200-year record of freshwater availability for regions in western North America fed by high-elevation runoff. *Geophysical Research Letters* **38**: 10.1029/2011GL047599.

Sauchyn *et al*. (2011) observed "a growing demand for the surface water resources of the Canadian Prairie Provinces has resulted in increasing vulnerability to hydrological drought," citing the studies of Schindler and Donahue (2006) and Wheaton *et al*. (2008). They further noted "a shift in the amount and timing of streamflow represents the most serious risk from recent and projected climate warming in western Canada (Sauchyn *et al*., 2010)" and "the Saskatchewan River Basin is among Canada's most vulnerable watersheds, in terms of projected climate changes and impacts, and the sensitivity of natural systems and economic activities to Canada's most variable hydroclimate." It is, of course, important to know the characteristics of past streamflow variability in order to better prepare for future droughts and to determine whether extreme droughts that may occur in the future might be due to CO_2-induced global warming or are within the range of natural variability experienced in the past, when the air's CO_2 concentration was both much lower and less variable than it is currently. Is a mere century of real-world data sufficient for these purposes?

In a study designed to explore this question by determining whether streamflow variability recorded by the streamflow gauge at Edmonton, Alberta (Canada) during the past century (since 1912) is representative of the range of variability experienced there during the past millennium, Sauchyn *et al*. developed a 945-year reconstruction of the annual flow of the Northern Saskatchewan River based on tree rings collected from seven sites within the runoff-generating upper basin of the river (Figure 7.4.4.1.2).

The Edmonton stream-gauge record clearly does not "represent the full extent of interannual to multidecadal variability in the tree-ring data," for as noted by Sauchyn *et al*. "there are periods of low flow in the pre-instrumental record that are longer and more severe than those recorded by the gauge" and which "pre-date Euro-Canadian settlement of the region." Two of these extreme events were droughts of approximately 30 years' duration, one in the early 1700s and another during the mid-1100s. One of the two most prominent megadroughts lasted for most of the fourteenth century, while the other occurred in the latter part of the fifteenth century.

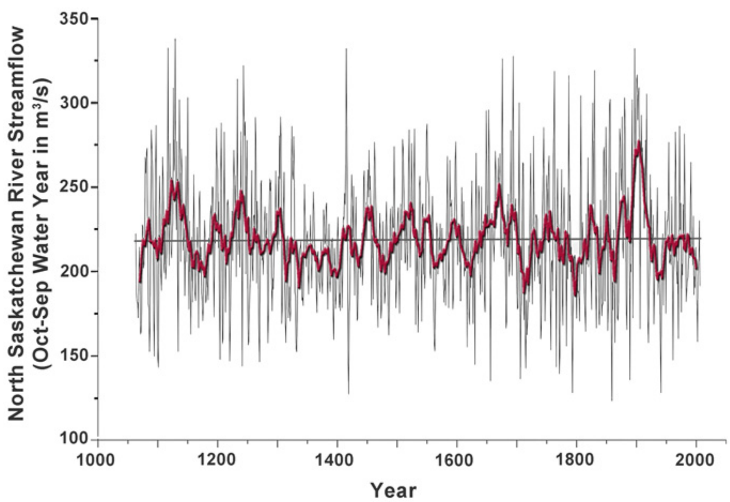

Figure 7.4.4.1.2. North Saskatchewan River reconstructed water year (October to September) flow for the period 1063–2006. Adapted from Sauchyn, D., Vanstone, J., and Perez-Valdivia, C. 2011. Modes and forcing of hydroclimatic variability in the upper North Saskatchewan River Basin since 1063. *Canadian Water Resources Journal* **36**: 205–218.

Sauchyn *et al*. observe "there is less certainty and stationarity in western [Canadian] water supplies than implied by the instrumental record," which is "the conventional basis for water resource management and planning" of the region. Their streamflow reconstruction provides an improved basis for determining the uniqueness of whatever future droughts might occur throughout the region. Their work also makes it more difficult to claim such droughts were caused by anthropogenic CO_2 emissions, since there was far less CO_2 in Earth's atmosphere prior to the 1912 start date of the region's prior streamflow history, when several droughts far more serious than those of the past century occurred.

Laird *et al*. (2012) wrote "future extreme droughts, similar to or more extreme than the 'dust-bowl' 1930s, could be the most pressing problem of global warming," citing Romm (2011) and noting, for comparison, "droughts of unusually long duration" or megadroughts that occurred during the Medieval Climate Anomaly (MCA) "lasted for several decades to centuries thus dwarfing modern-day droughts," as reported by Seager *et al*. (2007) and Cook *et al*. (2010).

Observing "one of the predictions of increasing temperatures is decreased lake levels and river flows (Schindler and Lee, 2010)," the eight researchers stated "analysis of longer-term records of past water levels can provide a context for informing water managers on the inherent natural variability of lake levels and their sensitivity to climate change." They described a pertinent study they conducted on six lakes spread across a 250-km transect of the Winnipeg River Drainage Basin of northwest Ontario, Canada, where the land-based pollen data of Viau and Gajewski (2009) suggest the presence of warmer temperatures during the MCA.

The diatom-inferred decadal-scale two-millennia-long drought records, which Laird *et* *al*. developed for the six lakes they studied, revealed what they call "periods of synchronous change" had occurred across the six lakes throughout "a period of prolonged aridity during the MCA (c. 900–1400 CE)." They reported this "general synchrony across sites suggests an extrinsic climate forcing (Williams *et al*., 2011)," with the MCA being part of a set of what they call "inherent natural fluctuations."

Laird *et al*. also noted "a widespread external forcing must be large enough for regional patterns to emerge." In the Nebraska Sandhills, they reported, "an analysis of five topographically closed lakes indicated relative coherency over the last 4,000 years, particularly during the MCA with all lakes indicating lake-level decline (Schmieder *et al*., 2011)." In addition, "in Minnesota, sand deposits in Mina Lake indicate large declines in lake level during the 1300s (St. Jacques *et al*., 2008), high eolian deposition occurred from ~1280 to 1410 CE in Elk Lake (Dean, 1997) and $\delta^{18}O$ from calcite indicated an arid period from ~1100 to 1400 CE in Steel Lake (Tian *et al*., 2006)," while "in Manitoba, the cellulose $\delta^{18}O$ record from the southern basin of Lake Winnipeg indicated severe dry conditions between 1180 and 1230 CE, and a less-severe dry period from 1320 to 1340 CE (Buhay *et al*., 2009)." Relatively warm conditions during the MCA, they added, "have been inferred from pollen records in the central boreal region of Canada and in Wisconsin," citing Viau and Gajewski (2009), Viau *et al*. (2012), and Wahl *et al*. (2012).

These findings have important implications. Most germane to climatology is this: If future extreme droughts, such as those that occurred during the MCA, could indeed be the "most pressing problem" of projected future global warming, as many contend, then it logically follows the Medieval Warm Period must have been far more extreme in terms of high temperature values and their duration than anything yet experienced during the Current Warm Period. That observation is strong evidence that warming considerably in excess of what has been experienced to date in the CWP can occur without any help from rising atmospheric CO_2 concentrations, which were more than 100 ppm less during the Medieval Warm Period than they are today. The great warmth of the MWP is demonstrated by the quantitative and qualitative findings of a host of scientists who have studied the Medieval and Current Warm Periods (see Chapter 4 of this report), all of which further suggests the development of the planet's Current Warm Period may be due to something entirely unrelated to anthropogenic CO_2 emissions.

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7.4.4.2 Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Mexico.

Stahle *et al*. (2000) developed a long-term history of drought over much of North America from reconstructions of the Palmer Drought Severity Index, based on analyses of many lengthy tree-ring records. This history revealed the occurrence of a sixteenth century drought in Mexico that persisted from the 1540s to the 1580s. The authors observed "the 'megadrought' of the 16th century far exceeded any drought of the 20th century."

Diaz *et al*. (2002) constructed a history of winter-spring (November–April) precipitation—which accounts for one-third of the yearly total—for the Mexican state of Chihuahua for the period 1647–1992, based on earlywood width chronologies of more than 300 Douglas fir trees growing at four locations along the western and southern borders of Chihuahua and at two locations in the United States just above Chihuahua's northeast border. They noted "three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century." Although this observation tends to make the twentieth century look highly anomalous in this regard, it is not; two of those three worst drought years occurred during a period of average to slightly above-average precipitation.

Diaz *et al*. also noted "the longest drought indicated by the smoothed reconstruction lasted 17 years (1948–1964)," again indicative of abnormally dry conditions during the twentieth century. However, for several of the 17 years of that below-normal-precipitation interval, precipitation values were only slightly below normal. Four very similar dry periods were interspersed throughout the preceding two and a half centuries: one in the late 1850s and early 1860s, one in the late 1790s and early 1800s, one in the late 1720s and early 1730s, and one in the late 1660s and early 1670s.

In the twentieth century, there also was a long period of high winter-spring precipitation from 1905 to 1932, and following the major drought of the 1950s, precipitation remained at or just slightly above normal for the remainder of the record. With respect to the entire 346 years, Diaz *et al*. found no long-term trend in the data, nor was there evidence of any sustained departure from that trend during the twentieth century, indicating neither twentieth century anthropogenic CO_2 emissions nor twentieth century warming significantly affected rainfall in the Mexican state of Chihuahua.

Cleaveland *et al*. (2003) constructed a winter-spring (November–March) precipitation history for the period 1386–1993 for Durango, Mexico based on earlywood width chronologies of Douglas-fir tree rings collected at two sites in the Sierra Madre Occidental. They reported this record "shows droughts of greater magnitude and longer duration than the worst historical drought that occurred in the 1950s and 1960s." These earlier dramatic droughts included the long dry spell of the 1850s–1860s and what they call the megadrought of the mid- to late-sixteenth century. Their work demonstrates the worst droughts of the past 600 years did not occur during the period of greatest warmth. Instead, they occurred during the Little Ice Age, perhaps the coldest period of the current interglacial.

Hodell *et al*. (2005b) analyzed a 5.1-m sediment core they retrieved from Aguada X'caamal, a small sinkhole lake in northwest Yucatan, Mexico, finding an important hydrologic change occurred there during the fifteenth century AD. The change was documented by the appearance of *A. beccarii* in the sediment profile, a decline in the abundance of charophytes, and an increase in the $\delta^{18}O$ of gastropods and ostracods. In addition, they reported "the salinity and ^{18}O content of the lake water increased as a result of reduced precipitation and/or increased evaporation in the mid- to late 1500s." These changes, as well as many others they cited, were "part of a larger pattern of oceanic and atmospheric change associated with the Little Ice Age that included cooling throughout the subtropical gyre (Lund and Curry, 2004)." They wrote, the "climate became drier on the Yucatan Peninsula in the 15th century AD near the onset of the Little Ice Age," as is also suggested by Maya and Aztec chronicles that "contain references to cold, drought and famine in the period AD 1441–1460."

Hodell *et al*. (1995) provided evidence for a protracted drought during the Terminal Classic Period of Mayan civilization (AD 800–1000), based on their analysis of a sediment core retrieved in 1993 from Lake Chichanacanab in the center of Mexico's northern Yucatan Peninsula. Subsequently, based on two additional sediment cores retrieved from that location in 2000, Hodell *et al*. (2001) determined the massive drought likely occurred in two distinct phases (750–875 and 1000–1075). Reconstructing the climatic history of the region over the past 2,600 years and applying spectral analysis to the data also revealed a significant recurrent drought periodicity of 208 years that matched well with a cosmic ray-produced ^{14}C record preserved in tree rings. This periodicity is believed to reflect variations in solar activity; because of the good correspondence between the two datasets, Hodell *et al.* concluded "a significant component of century-scale variability in Yucatan droughts is explained by solar forcing."

Hodell *et al*. (2005a) returned to Lake Chichanacanab in March 2004 and retrieved a number of additional sediment cores in some of the deeper parts of the lake. The scientists took multiple cores from the lake's deepest location, from which they obtained depth profiles of bulk density by means of gamma-ray attenuation as well as profiles of reflected red, green, and blue light via a digital color line-scan camera. They observed, "the data reveal in great detail the climatic events that comprised the Terminal Classic Drought and coincided with the demise of Classic Maya civilization." They reported "the Terminal Classic Drought was not a single, two-century-long megadrought, but rather consisted of a series of dry events separated by intervening periods of relatively moister conditions," and it "included an early phase (ca 770–870) and late phase (ca 920–1100)." They found "the bipartite drought history inferred from Chichancanab is supported by oxygen isotope records from nearby Punta Laguna" and "the general pattern is also consistent with findings from the Cariaco Basin off northern Venezuela (Haug *et al*., 2003), suggesting that the Terminal Classic Drought was a widespread phenomenon and not limited to north-central Yucatan."

Concurrent with the study of Hodell *et al*. (2005a), Almeida-Lenero *et al*. (2005) analyzed pollen profiles derived from sediment cores retrieved from Lake Zempoala and nearby Lake Quila in the central Mexican highlands approximately 65 km southwest of Mexico City. The scientists determined it was generally more humid than at present in the central Mexican highlands during the mid-Holocene. Thereafter, however, there was a gradual drying of the climate. Their data from Lake Zempoala indicated "the interval from 1300 to 1100 cal yr BP was driest and represents an extreme since the mid-Holocene." They further noted this interval of 200 years "coincides with the collapse of the Maya civilization." They reported their data from Lake Quila were "indicative of the most arid period reported during the middle to late Holocene from c. 1300 to 1100 cal yr BP." In addition, they noted "climatic aridity during this time was also noted by Metcalfe *et al*. (1991) for the Lerma Basin [central Mexico]" and "dry climatic conditions were also reported from Lake Patzcuaro, central Mexico by Watts and Bradbury (1982)." The "dry conditions were also reported for [Mexico's] Zacapu Basin (Metcalfe, 1995) and for [Mexico's] Yucatan Peninsula (Curtis *et al*., 1996, 1998; Hodell *et al*., 1995, 2001)."

Therrell *et al*. (2006) "developed a continuous, exactly dated, tree-ring reconstruction of maize yield variability" over the period 1474 to 2001 in an effort to provide "new insight into the history of climate and food availability in the heartland of the Mesoamerican cultural province." They relied on latewood-width data derived from "the second-most southerly native stand of Douglas-fir (*Pseudtosuga menziesii*) trees known in the Americas" and compared their reconstruction to "historical records of crop failure and famine in order to cross-validate the tree-ring and historical records."

Therrell *et al*.'s plot of reconstructed drought-induced maize-yield anomalies exposed seven major decadal-scale yield shortfalls over the past 500 years, with a mean rate of occurrence of 1.5 per century over the 400-year period AD 1500–1900. In the twentieth century, there was only one such multiyear famine, and its magnitude paled in comparison to that of the average such event of the preceding four centuries.

Metcalfe and Davies (2007) synthesized the findings of a variety of paleoclimate studies based on analyses of the sediment records of several crater lakes and lakes formed by lava dams scattered across the Trans Mexican Volcanic Belt of central Mexico with an absolute chronology provided by radiocarbon dates extending back to 1500 ^{14}C yr BP. Noting the degree of coherence among the records "is remarkable," Metcalf and Davis reported "dry conditions, probably the driest of the Holocene, are recorded over the period 1400 to 800 ^{14}C yr BP (ca. AD 700–1200)." The authors reported the results were "consistent with results from the Yucatan Peninsula (Hodell *et al*., 1995, 2005) ... and from the Cariaco basin (Haug *et al*., 2003) and the Isthmus of Panama (Lachniet *et al*., 2004)."

Dominguez-Vazquez and Islebe (2008) derived a 2,000-year history of regional drought for the Lacandon Forest Region in the state of Chiapas, southeastern Mexico. Based on radiocarbon dating and pollen analyses of a sediment core retrieved from the shore of Naja Lake (16°59'27.6"N, 91°35'29.6"W), the two authors reported "a marked increase in *Pinus* pollen, together with a reduction in lower montane rain forest taxa, [which they] interpreted as evidence for a strong, protracted drought from 1260 to 730 years BP," which they characterized as "the most severe" while noting it "coincides with the Maya classic collapse."

Escobar *et al*. (2010) examined sediment cores from Lakes Punta Laguna, Chichancanab, and Peten Itza on the Yucatan Peninsula as a proxy measure for high-frequency climate variability. The five researchers found "relatively dry periods were persistently dry, whereas relatively wet periods were composed of wet and dry times." They noted their findings "confirm the interpretations of Hodell *et al*. (1995, 2007) and Curtis *et al*. (1996) that there were persistent dry climate episodes associated with the Terminal Classic Maya Period." They found "the Terminal Classic Period from ca. AD 910 to 990 was not only the driest period in the last 3,000 years, but also a persistently dry period." In further support of this interpretation, they note "the core section encompassing the Classic Maya collapse has the lowest sedimentation rate among all layers and the lowest oxygen isotope variability."

Figueroa-Rangel *et al*. (2010) used fossil pollen, microfossil charcoal, and organic and inorganic sediment data obtained from a 96-cm core of black organic material retrieved from a small forest hollow (19°35'32"N, 104°16'56"W) to construct a 1,300-year history of cloud forest vegetation dynamics in the Sierra de Manantlan Biosphere Reserve (SMBR, in west-central Mexico). The authors found "during intervals of aridity, cloud forest taxa tend to become reduced," whereas "during intervals of increased humidity, the cloud forest thrives." They determined there was a major dry period from approximately AD 800 to 1200 in the SMBR and observed "results from this study corroborate the existence of a dry period from 1200 to 800 cal years BP in mountain forests of the region (B.L. Figueroa-Rangel, unpublished data); in central Mexico (Metcalf and Hales, 1994; Metcalfe, 1995; Arnauld *et al*., 1997; O'Hara and Metcalfe, 1997; Almeida-Lenero *et al*., 2005; Ludlow-Wiechers *et al*., 2005; Metcalfe *et al*., 2007); lowlands of the Yucatan Peninsula (Hodell *et al*., 1995, 2001, 2005a,b) and the Cariaco Basin in Venezuela (Haug *et al*., 2003)." In addition, they reported "the causes associated to this phase of climate change have been attributed to solar activity (Hodell *et al*., 2001; Haug *et al*., 2003), changes in the latitudinal migration of the Intertropical Convergence Zone (ITCZ, Metcalfe *et al*., 2000; Hodell *et al*., 2005a,b; Berrio *et al*., 2006) and to ENSO variability (Metcalfe, 2006)."

Throughout much of Mexico, some of the driest conditions and worst droughts of the Late Holocene occurred prior to the late twentieth and early twenty-first centuries. These observations contradict assertions that global warming will cause drought conditions to worsen, especially considering the Mexican droughts of the twentieth century and early twenty-first century were much milder than many of that occurred during the much colder centuries of the Little Ice Age and the warmer Medieval Warm Period. The latter observation suggests that to attribute warmth as the cause of droughts means acknowledging the Medieval Warm Period extended beyond the North Atlantic and was significantly warmer than current and recent temperatures.

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7.4.4.3 United States

7.4.4.3.1 Central

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the central United States.

The United States' Northern Great Plains is an important agricultural region of North America, providing a significant source of grain both locally and internationally. It is susceptible to extreme droughts that tend to persist longer than in any other region of the country (Karl *et al*., 1987; Soule, 1992), making it a good place to review the history of drought to determine whether the region is currently experiencing a manifestation of the model-based claim (Gore, 2006; Mann and Kump, 2008) that global warming will usher in a period of more frequent and intense drought.

Mauget (2004) looked for what he called "initial clues" to the commencement of the great drying of the U.S. heartland predicted to occur in response to CO_2-induced global warming by Manabe and Wetherald (1987), Rind *et al*. (1990), Rosenzweig and Hillel (1993), and Manabe *et al*. (2004), which Mauget reasoned would be apparent in the observational streamflow record of the region. He employed data obtained from the archives of the U.S. Geological Survey's Hydro-Climatic Data Network, 42 stations covering the central third of the United States stretching from the Canadian border on the north to the Gulf of Mexico on the south, with the densest coverage existing within the U.S. corn belt.

Mauget found "an overall pattern of low flow periods before 1972, and high flow periods occurring over time windows beginning after 1969." Of the 42 stations' high flow periods, he observed "34 occur during 1969–1998, with 25 of those periods ending in either 1997 or 1998," and "of those 25 stations 21 are situated in the key agricultural region known as the Corn Belt." He also found "among most of the stations in the western portions of the Corn Belt during the 1980s and 1990s there is an unprecedented tendency toward extended periods of daily high flow conditions, which lead to marked increases in the mean annual frequency of hydrological surplus conditions relative to previous years." Furthermore, he found "in 15 of the 18 Corn Belt gage stations considered here at daily resolution, a more than 50% reduction in the mean annual incidence of hydrological drought conditions is evident during those periods." Finally, Mauget reported "the gage station associated with the largest watershed area—the Mississippi at Vicksburg—shows more than a doubling of the mean annual frequency of hydrological surplus days during its 1973–1998 high flow period relative to previous years, and more than a 50% reduction in the mean annual incidence of hydrological drought condition."

Mauget observed the overall pattern of climate variation "is that of a reduced tendency to hydrological drought and an increased incidence of hydrological surplus over the Corn Belt and most of the Mississippi River basin during the closing decades of the 20th century." He further noted "some of the most striking evidence of a transition to wetter conditions in the streamflow analyses is found among streams and rivers situated along the Corn Belt's climatologically drier western edge."

Do such findings represent the early stages of real-world climate change? Mauget found the streamflow data do indeed "suggest a fundamental climate shift, as the most significant incidence of high ranked annual flow was found over relatively long time scales at the end of the data record." That shift, however, is *away from* more frequent and severe drought.

Shapley *et al*. (2005) undertook a longer-term study of the topic, developing a 1,000-year hydro-climate reconstruction from local bur oak tree-ring records and various lake sediment cores in the Northern Great Plains. Prior to 1800, they determined, "droughts tended towards greater persistence than during the past two centuries," suggesting droughts of the region became shorter-lived as opposed to longer-lasting as Earth gradually recovered from the cold temperatures of the Little Ice Age.

Daniels and Knox (2005) analyzed the alluvial stratigraphic evidence for an episode of major channel incision in tributaries of the upper Republican River occurring between 1100 and 800 years ago, after which they compared their findings with proxy drought records from 28 other locations throughout the Great Plains and surrounding regions. This work revealed channel incision in the Republican River between approximately AD 900 and 1200 was well correlated with a multi-centennial episode of widespread drought, which in the words of Daniels and Knox "coincides with the globally recognized Medieval Warm Period." Modern twentieth century warming has not led to a repeat of those widespread drought conditions.

Stambaugh *et al*. (2011) "used a new long tree-ring chronology developed from the central U.S. to reconstruct annual drought and characterize past drought duration, frequency, and cycles in the agriculturally important U.S. Corn Belt region during the last millennium." They calibrated and verified this chronology against monthly values of the instrumental Palmer Hydrologic Drought Index during the summer season of June, July, and August. The six scientists reported "20th century droughts, including the Dust Bowl, were relatively unremarkable when compared to drought durations prior to the instrumental record." They noted, for example, the nineteenth century was the driest of the past millennium, with major drought periods occurring from about 1816 to 1844 and 1849 to 1880, during what they described as the transition out of the Little Ice Age. Prior to that, there had been 45 years of drought in the latter part of the seventeenth century coincident with the Maunder Minimum of solar activity, which is associated with the coldest period of the current interglacial.

Going back further in time, Stambaugh *et al*. found an approximately 35-year drought in the mid- to late-fifteenth century during "a period of decreased radiative forcing and northern hemisphere temperatures." Eclipsing them all, however, was "the approximately 61-year drought in the late 12th century (ca. AD 1148-1208)," which "appears to be the most significant drought of the entire reconstruction" and in fact "corresponds to the single greatest megadrought in North America during the last 2000 years (Cook *et al*., 2007)," as well as "unmatched persistent low flows in western U.S. river basins (Meko *et al*., 2007)." This drought, the authors reported, occurred during the middle of the Medieval Warm Period—"an interval of warmer temperatures between approximately AD 800–1300 characterized by greater drought duration and frequency in the Northern Great plains compared to more modern times."

Stambaugh *et al.*'s findings show there is nothing unusual, unnatural, or unprecedented about any twentieth or twenty-first century droughts that may have hit the agricultural heartland of the United States. It is also clear the much greater droughts of the past millennium occurred during periods of both relative cold and relative warmth, as well as the transitions between them.

Forman *et al.* (2005) observed "periods of dune reactivation reflect sustained moisture deficits for years to decades and reflect broader environmental change with diminished surface- and ground-water resources," which prompted them to focus on "the largest dune system in North America, the Nebraska Sand Hills." They utilized "recent advances in optically stimulated luminescence dating (Murray and Wintle, 2000) to improve chronologic control on the timing of dune reactivation" while linking landscape response to drought over the past 1,500 years to tree-ring records of aridity.

Forman *et al.* identified six major aeolian depositional events in the past 1,500 years, all but one of which (the 1930s "Dust Bowl" drought) occurred prior to the twentieth century. Moving back in time from the Dust Bowl, the preceding three major events occurred during the depths of the Little Ice Age, near the Little Ice Age's inception, and near the end of the Dark Ages Cold Period. As for how the earlier droughts compared with those of the past century, the researchers found the 1930s drought (the twentieth century's worst depositional event) was less severe than the others, especially the sixteenth century megadrought. Forman *et al.* concluded the aeolian landforms "are clear indicators of climate variability beyond twentieth century norms, and signify droughts of greater severity and persistence than thus far instrumentally recorded." Their study also reveals post-Little Ice Age warming—which is often claimed to be unprecedented over the past two millennia—has not produced similarly unprecedented droughts.

Advancing the field of study back further in time, Woodhouse and Overpeck (1998) reviewed what is known about the frequency and severity of drought in the central United States over the past 2,000 years based upon empirical evidence of drought from various proxy indicators. Their study indicated the presence of numerous "multidecadal- to century-scale droughts," leading them to conclude "twentieth-century droughts are not representative of the full range of drought variability that has occurred over the last 2000 years." In addition, they observed the twentieth century was characterized by droughts of "moderate severity and comparatively short duration, relative to the full range of past drought variability."

With respect to the causes of drought, Woodhouse and Overpeck suggested there might be several either directly or indirectly inducing changes in atmospheric circulation and moisture transport. They cautioned "the causes of droughts with durations of years (i.e., the 1930s) to decades or centuries (i.e., paleodroughts) are not well understood." Hence, they concluded, "the full range of past natural drought variability, deduced from a comprehensive review of the paleoclimatic literature, suggests that droughts more severe than those of the 1930s and 1950s are likely to occur in the future." This is likely to be the case irrespective of future atmospheric CO_2 concentrations or temperatures.

Fritz *et al.* (2000) constructed three 2,000-year histories of lake-water salinity at three sites in North Dakota—Moon Lake, Coldwater Lake, and Rice Lake—to infer regional patterns of drought and comment on its potential cause. "From the vantage point of the 20th century," they observed, "the three North Dakota sites suggest that droughts equal or greater in magnitude to those of the Dust Bowl period were a common occurrence during the last 2000 years and that severe droughts may have been frequent for multiple decades within this period." In addition, they reported "studies from the northern Great Plains and western North America (Cook *et al.*, 1997; Dean, 1997; Laird *et al.*, 1996; Yu and Ito, 1999) have shown a correlation between solar forcing and centennial- and decadal-scale drought patterns." They conclude "solar variability may influence the duration of dry periods through its impact on convective activity and circulation (Rind and Overpeck, 1993)."

Laird *et al.* (1998) examined the region's historical record of drought in an attempt to establish a baseline of natural drought variability that could help in attempts to determine whether current and future droughts might be anthropogenically influenced. Working with a high-resolution sediment core obtained from Moon Lake, North Dakota, which provided a subdecadal record of salinity (drought) over the past 2,300 years, they discovered the U.S. Northern Great Plains were relatively wet during the final 750 years of this period. Throughout the 1,550 prior years, Laird *et al*. found "recurring severe droughts were more the norm" and were "of much greater intensity and duration than any in the 20th century," including the great Dust Bowl event of the 1930s. Consequently, and in light of their finding "no modern equivalents" to Northern Great Plains droughts experienced prior to AD 1200, it would appear twentieth century global warming has had no effect on drought conditions in this part of the world.

Tian *et al*. (2006) derived a 31-century high-resolution $\delta^{18}O$ record of aridity from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. Among their findings, they noted "the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods." Most striking, they found "drought variability was anomalously low during the 20th century"—so depressed that "~90% of the variability values during the last 3100 years were greater than the 20th-century average."

The above findings show there is nothing unusual, unnatural, or unprecedented about recent droughts in the Central United States. Droughts of greater duration and intensity have occurred numerous times in the past. Claims of increasing future drought as a result of global warming are not supported by real-world data, as modern global warming has, if anything, tended to lessen drought conditions throughout the central United States.

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7.4.4.3.2 Eastern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the eastern United States.

Pederson *et al*. (2012) note drought is "a pervasive phenomenon throughout much of North America with profound ecological and societal implications," as has been suggested by the work of Hursh and Haasis (1931), Breshears *et al*. (2005), Manuel (2008), and Allen *et al*. (2010). Citing Knight (2004) and Seager *et al*. (2009), they report recent moisture deficits in the southeastern United States have renewed water management challenges that underscore the need to "better understand drought processes in humid, subtropical regions." Pederson *et al*. attempted "to put the region's recent drought variability in a long-term perspective" by reconstructing historic drought trends in the Apalachicola-Chattahoochee-Flint river basin over the period 1665–2010 using a dense and diverse tree-ring network. This network, they wrote, "accounts for up to 58.1% of the annual variance in warm-season drought during the 20th century and captures wet eras during the middle to late 20th century."

The 12 researchers found the Palmer Drought Severity Index reconstruction for their study region revealed "recent droughts are not unprecedented over the last 346 years" and "droughts of extended duration occurred more frequently between 1696 and 1820," when most of the world was in the midst of the Little Ice Age. They also found their results "confirm the findings of the first reconstruction of drought in the southern Appalachian Mountain region, which indicates that the mid-18th and early 20th centuries were the driest eras since 1700," citing Stahle *et al*. (1988), Cook *et al*. (1998), and Seager *et al*. (2009).

Quiring (2004) introduced his study of the subject by describing the drought of 2001–2002, which by June of the latter year produced anomalously dry conditions along most of the east coast of the country, including severe drought conditions from New Jersey to northern Florida forcing 13 states to ration water. Shortly after the drought began to subside in October 2002, however, moist conditions returned and persisted for about a year, producing the wettest growing-season of the instrumental record. These observations, in Quiring's words, "raise some interesting questions," including, "are moisture conditions in this region becoming more variable?"

Using an 800-year tree-ring-based reconstruction of the Palmer Hydrological Drought Index, Quiring documented the frequency, severity, and duration of growing-season moisture anomalies in the southern mid-Atlantic region of the United States. Among other things, this work revealed "conditions during the 18th century were much wetter than they are today, and the droughts that occurred during the 16th century tended to be both longer and more severe." He concluded "the recent growing-season moisture anomalies that occurred during 2002 and 2003 can only be considered rare events if they are evaluated with respect to the relatively short instrumental record (1895–2003)." When compared to the 800-year reconstructed record, he observed, "neither of these events is particularly unusual." In addition, Quiring reported, "although climate models predict decreases in summer precipitation and significant increases in the frequency and duration of extreme droughts, the data indicate that growing-season moisture conditions during the 20th century (and even the last 19 years) appear to be near normal (well within the range of natural climate variability) when compared to the 800-year record."

Cronin *et al*. (2000) studied the salinity gradient across sediment cores from Chesapeake Bay, the largest estuary in the United Sates, in an effort to examine precipitation variability in the surrounding watershed during the past millennium. Their work revealed the existence of a high degree of decadal and multidecadal variability between wet and dry conditions throughout the 1,000-year record, when regional precipitation totals fluctuated by 25 to 30%, often in "extremely rapid [shifts] occurring over about a decade." In addition, precipitation over the last two centuries of the record was generally greater than it was during the previous eight centuries, with the exception of the Medieval Warm Period (AD 1250–1350), when the local climate was found to be "extremely wet." The 10 researchers also found the region experienced several "megadroughts" that lasted for 60 to 70 years, several of which were "more severe than twentieth century droughts."

Willard et al. (2003) built upon the work of Cronin *et al*., examining the last 2,300 years of the Holocene record for Chesapeake Bay and the adjacent terrestrial ecosystem "through the study of fossil dinoflagellate cysts and pollen from sediment cores." They found "several dry periods ranging from decades to centuries in duration are evident in Chesapeake Bay records." The first of these periods of lower-than-average precipitation (200 BC–AD 300) occurred during the latter part of the Roman Warm Period, and the next such period (~AD 800–1200) "corresponds to the 'Medieval Warm Period.'" In addition, they identified several decadal-scale dry intervals spanning the years AD 1320–1400 and 1525–1650.

Willard *et al*. noted "mid-Atlantic dry periods generally correspond to central and southwestern USA 'megadroughts', which are described by Woodhouse and Overpeck (1998) as major droughts of decadal or more duration that probably exceeded twentieth-century droughts in severity." They observed "droughts in the late sixteenth century that lasted several decades, and those in the 'Medieval Warm Period' and between ~AD 50 and AD 350 spanning a century or more have been indicated by Great Plains tree-ring (Stahle *et al*., 1985; Stahle and Cleaveland, 1994), lacustrine diatom and ostracode (Fritz *et al*., 2000; Laird *et al*., 1996a, 1996b) and detrital clastic records (Dean, 1997)." Their work in the eastern United States, together with the work of researchers in other parts of the country, demonstrates twentieth-century global warming has not led to the occurrence of unusually strong wet or dry periods.

Springer *et al*. (2008) constructed a multidecadal-scale history of east-central North America's hydroclimate covering the past 7,000 years, based on Sr/Ca ratios and $\delta^{13}C$ data obtained from stalagmite BCC-002 of Buckeye Creek Cave (BCC) in West Virginia, USA. The authors detected seven significant mid- to late-Holocene droughts that "correlate with cooling of the Atlantic and Pacific Oceans as part of the North Atlantic Ocean ice-rafted debris [IRD] cycle, which has been linked to the solar irradiance cycle," as per Bond *et al*. (1997, 2001). In addition, they found "the Sr/Ca and $\delta^{13}C$ time series display periodicities of ~200 and ~500 years," "the ~200-year periodicity is consistent with the de Vries (Suess) solar irradiance cycle," and the ~500-year periodicity is likely "a harmonic of the IRD oscillations." They also reported "cross-spectral analysis of the Sr/Ca and IRD time series yields statistically significant coherencies at periodicities of 455 and 715 years," and these latter values "are very similar to the second (725-years) and third (480-years) harmonics of the 1450 ± 500-years IRD periodicity." Such findings "corroborate works indicating that millennial-scale solar-forcing is responsible for droughts and ecosystem changes in central and eastern North America (Viau *et al*., 2002; Willard *et al*., 2005; Denniston *et al*., 2007)." Their high-resolution time series also "provide much stronger evidence in favor of solar-forcing of North American drought by yielding unambiguous spectral analysis results."

Palaeoclimate data from the eastern United States, as highlighted in this section, show droughts are not becoming more extreme and erratic in response to global warming.

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7.4.4.3.3 Western

7.4.4.3.3.1 Pacific Northwest

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Pacific Northwest region of the United States.

Knapp *et al*. (2002) created a 500-year history of severe single-year Pacific Northwest droughts from a study of 18 western juniper tree-ring chronologies identifying what they call extreme Climatic Pointer Years, or CPYs, indicative of severe single-year droughts. This procedure revealed “widespread and extreme CPYs were concentrated in the 16th and early part of the 17th centuries,” and “both the 18th and 19th centuries were largely characterized by a paucity of drought events that were severe and widespread.” Thereafter, however, “CPYs became more numerous during the 20th century,” although the number of twentieth century extreme CPYs (26) was still substantially less than the mean of sixteenth and seventeenth century extreme CPYs (38), when the planet was considerably colder.

Gedalof *et al*. (2004) used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water-year flow since 1750 on the Columbia River at The Dales in Oregon. They conducted this study of the second largest drainage basin in the United States “for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events.” The study revealed “persistent low flows during the 1840s were probably the most severe of the past 250 years” and “the drought of the 1930s is probably the second most severe.”

More recent droughts, in the words of the researchers, “have led to conflicts among uses (e.g., hydroelectric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of access to water (in particular junior water rights holders in the agricultural sector).” Nevertheless, they observed, “these recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events.” They also found “the period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events,” demonstrating Pacific Northwest droughts have not become more severe or long-lasting as temperatures rose during the twentieth century.

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7.4.4.3.3.2 Idaho/Montana/Wyoming

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Idaho, Montana, and Wyoming in the United States.

Wise (2010) noted “the 1667 km Snake River is one of the largest rivers in the United States, draining a semiarid region that covers 283,000 km^2 [and] includes most of Idaho, as well as portions of Wyoming, Utah, Nevada, Oregon, and Washington.” She observed the river’s water has been “historically allocated almost entirely for agricultural irrigation” and the Snake River is “the largest tributary of the Columbia River (based on both discharge and watershed size),” which makes it “also important for users further downstream.” Wise reported “the 20th century was an abnormally wet period in this region (Gray and McCabe, 2010),” but an early twenty-first century drought “has raised questions about whether these dry conditions should be considered an extreme event or if this drought is within the range of natural variability.”

Wise utilized tree-ring samples collected near the headwaters of the Snake River in Wyoming augmented with preexisting tree ring chronologies to extend the short (1911–2006) instrumental water supply record of the region. This provided the first multi-century (1591–2005) record of the river's water supply variability, which could then provide context for the early twenty-first century drought in this region. She found "individual low-flow years in 1977 and 2001 and the longer-term 1930s Dust Bowl drought meet or exceed the magnitude of dry periods in the extended reconstructed period." In terms of overall severity, "the instrumental record does not contain a drought of the extent seen in the mid-1600s." Wise further observed "twenty-four of 34 years in the 1626–1659 time period had below-average flow, including periods of six and seven consecutive below-mean years (1626–1632 and 1642–1647)," and "during the most severe period from 1626 to 1647, 17 of 22 years (77%) were below-normal flow." She concluded "this type of event could represent a new 'worst-case scenario' for water planning in the upper Snake River."

Gray *et al*. (2004) used cores and cross sections from 79 Douglas fir and limber pine trees at four sites in the Bighorn Basin of north-central Wyoming and south-central Montana to develop a proxy for annual precipitation spanning the period AD 1260–1998. This reconstruction, in their words, "exhibits considerable nonstationarity, and the instrumental era (post-1900) in particular fails to capture the full range of precipitation variability experienced in the past ~750 years." They found "both single-year and decadal-scale dry events were more severe before 1900" and "dry spells in the late thirteenth and sixteenth centuries surpass both [the] magnitude and duration of any droughts in the Bighorn Basin after 1900." They observed "single- and multi-year droughts regularly surpassed the severity and magnitude of the 'worst-case scenarios' presented by the 1930s and 1950s droughts."

In a study covering a much longer period of time, Persico and Meyer (2009) studied "beaver-pond deposits and geomorphic characteristics of small streams to assess long-term effects of beavers and climate change on Holocene fluvial activity in northern Yellowstone National Park." They compared "the distribution of beaver-pond deposit ages to paleoclimatic proxy records in the Yellowstone region," finding "gaps in the beaver-pond deposit record from 2200–1800 and 700–1000 cal yr BP are contemporaneous with increased charcoal accumulation rates in Yellowstone lakes and peaks in fire-related debris-flow activity, inferred to reflect severe drought and warmer temperatures (Meyer *et al*., 1995)." In addition, they noted "the lack of evidence for beaver activity 700–1000 cal yr BP is concurrent with the Medieval Climatic Anomaly, a time of widespread multi-decadal droughts and high climatic variability in Yellowstone National Park (Meyer *et al*., 1995) and the western USA (Cook *et al*., 2004; Stine, 1998; Whitlock *et al*., 2003)." The lack of evidence for beaver activity 2200–1800 cal yr BP is concurrent with the Roman Warm Period. In both of these periods, the researchers concluded, the severe droughts "likely caused low to ephemeral discharges in smaller streams, as in modern severe drought," implying the Medieval and Roman Warm Periods were likely just as dry and warm as it is today.

These findings suggest there is nothing unusual, unnatural, or unprecedented about the degree of warmth and drought in the Current Warm Period. The regular recurrence of such drought conditions suggests their cause is a cyclical phenomenon of nature independent of the activities of the planet's human population.

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7.4.4.3.3.3 Nevada/Utah

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Nevada and Utah in the United States.

Benson *et al*. (2002) developed continuous high-resolution $\delta^{18}O$ records from cored sediments of Pyramid Lake, Nevada, which they used to help construct a 7,600-year history of droughts throughout the surrounding region. Oscillations in the hydrologic balance evident in this record occurred, on average, about every 150 years, but with significant variability. Over the most recent 2,740 years, for example, intervals between droughts ranged from 80 to 230 years, and drought durations ranged from 20 to 100 years. Some of the larger droughts forced mass migrations of indigenous peoples from lands that could no longer support them. In contrast, droughts of the historical instrumental record typically have lasted less than a decade.

Mensing *et al*. (2004) analyzed sediment cores for pollen and algal microfossils deposited at Pyramid Lake, Nevada during the prior 7,630 years, which allowed them to infer the hydrologic history of the area over that period. They found “sometime after 3430 but before 2750 cal yr B.P., climate became cool and wet,” but “the past 2500 yr have been marked by recurring persistent droughts.” The longest of these droughts “occurred between 2500 and 2000 cal yr B.P.,” and others occurred “between 1500 and 1250, 800 and 725, and 600 and 450 cal yr B.P,” with none recorded in more recent, warmer times.

The researchers also noted “the timing and magnitude of droughts identified in the pollen record compare favorably with previously published $\delta^{18}O$ data from Pyramid Lake” and with “the ages of submerged rooted stumps in the Eastern Sierra Nevada and woodrat midden data from central Nevada.” Finally, noting Bond *et al*. (2001) “found that over the past 12,000 yr, decreases in [North Atlantic] drift ice abundance corresponded to increased solar output,” they reported when they “compared the pollen record of droughts from Pyramid Lake with the stacked petrologic record of North Atlantic drift ice ... nearly every occurrence of a shift from ice maxima (reduced solar output) to ice minima (increased solar output) corresponded with a period of prolonged drought in the Pyramid Lake record.” Mensing *et al*. concluded “changes in solar irradiance may be a possible mechanism influencing century-scale drought in the western Great Basin [of the United States].”

Gray *et al*. (2004) used samples from 107 piñon pines at four sites in Utah to develop a proxy record of annual precipitation spanning the AD 1226–2001 interval for the Uinta Basin watershed in the northeastern portion of the state. This revealed “single-year dry events before the instrumental period tended to be more severe than those after 1900” and decadal-scale dry events were longer and more severe prior to 1900 as well. In particular, they found “dry events in the late 13th, 16th, and 18th Centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900.”

Considering the other end of the moisture spectrum, Gray *et al*. reported the twentieth century was host to two of the strongest wet intervals (1938–1952 and 1965–1987), although these periods were only the seventh and second most intense wet regimes, respectively, of the entire record. It would appear precipitation extremes (both high and low) in northeastern Utah’s Uinta Basin have become more attenuated as opposed to more amplified in conjunction with twentieth-century global warming.

MacDonald and Tingstad (2007) examined instrumental climate records to outline historical spatiotemporal patterns of precipitation variability in the Uinta Mountains, after which they “used tree-ring width chronologies from *Pinus edulis* Engelm (two-needle pinyon pine) trees growing near the northern and southern flanks of the mountains to produce an ~600-year reconstruction (AD 1405–2001) of Palmer Drought Severity Index [PDSI] for Utah Climate Division 5,” which they say “allows for the placement of 20th century droughts within the longer context of natural drought variability and also allows for the detection of long-term trends in drought.”

MacDonald and Tingstad reported “in the context of prolonged severe droughts," the twentieth century "has been relatively moist compared to preceding centuries." The scientists reported their PDSI reconstruction and the Uinta Basin precipitation reconstruction indicate "the early to mid 17th century in particular, and portions of the 18th and 19th centuries, experienced prolonged (>10 years) dry conditions that would be unusually severe by 20th century standards." They noted "the most striking example of widespread extended drought occurred during a ~45-year period between 1625 and 1670 when PDSI only rarely rose above negative values."

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7.4.4.3.3.4 California

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to California in the United States.

Malamud-Roam *et al*. (2006) conducted an extensive review of "the variety of paleoclimatic resources for the San Francisco Bay and watershed in order to identify major climate variations in the pre-industrial past, and to compare the records from the larger watershed region with the Bay records in order to determine the linkages between climate experienced over the larger watershed region and conditions in the San Francisco Bay." They found "intermittent mega-droughts of the Medieval Climate Anomaly (ca. AD 900–1350) coincided with a period of anomalously warm coastal ocean temperatures in the California Current," and "oxygen isotope compositions of mussel shells from archaeological sites along the central coast also indicate that sea surface temperatures were slightly warmer than present." In contrast, they noted "the Little Ice Age (ca. AD 1450–1800) brought unusually cool and wet conditions to much of the watershed," and "notably stable conditions have prevailed over the instrumental period, i.e., after ca. AD 1850, even including the severe, short-term anomalies experienced during this period," namely, "the severe droughts of the 1930s and the mid-1970s." When longer paleoclimate records are considered, they noted, "current drought conditions experienced in the US Southwest do not appear out of the range of natural variability." However, they speculated, "warmer temperatures associated with anthropogenic global warming may exacerbate such conditions," which would suggest current temperatures are not as warm as during the Medieval Warm Period.

In a study of "perfect drought" in Southern California (USA), MacDonald *et al*. (2008) defined the term as "a prolonged drought that affects southern California, the Sacramento River basin and the upper Colorado River basin simultaneously." They noted the instrumental record indicates the occurrence of such droughts throughout the past century, but they "generally persist for less than five years." That they have occurred at all, however, suggests the possibility of even longer perfect droughts, which could prove catastrophic for the region.

The three researchers explored the likelihood of such droughts occurring in the future based on dendrochronological reconstructions of the winter Palmer Drought Severity Index (PDSI) in southern California over the past thousand years, plus the concomitant annual discharges of the Sacramento and Colorado Rivers, under the logical assumption that what has occurred before may occur again. MacDonald *et al*. reported finding "prolonged perfect droughts (~30-60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th century during the period of the so-called 'Medieval Climate Anomaly.'" This led them to conclude "prolonged perfect droughts due to natural or anthropogenic changes in radiative forcing, are a clear possibility for the near future."

Kleppe *et al*. (2011) reconstructed the duration and magnitude of extreme droughts in the northern Sierra Nevada region based on dendrochronology, geomorphic analysis, and hydrologic modeling of the Fallen Leaf Lake (California) watershed in order to estimate paleo-precipitation near the headwaters of the Truckee River-Pyramid Lake watershed of eastern California and northwestern Nevada. The six scientists found "submerged Medieval trees and geomorphic evidence for lower shoreline corroborate a prolonged Medieval drought near the headwaters of the Truckee River-Pyramid Lake watershed," and water-balance calculations independently indicated precipitation was "less than 60% normal." They noted these findings "demonstrate how prolonged changes of Fallen Leaf's shoreline allowed the growth and preservation of Medieval trees far below the modern shoreline." In addition, they noted age groupings of such trees suggest similar megadroughts "occurred every 600–1050 years during the late Holocene."

The findings of Kleppe *et al*., and many others whose works they cite, suggest the Medieval Warm Period experienced substantially less precipitation and far longer and more severe drought than what has been experienced to date in the Current Warm Period. In addition, their data suggest such dry conditions have occurred regularly, in cyclical fashion, "every 650–1150 years during the mid- and late-Holocene." These observations suggest there is nothing unusual, unnatural, or unprecedented about the nature of drought during the Current Warm Period in the western United States.

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7.4.4.3.3.5 Colorado/Colorado River Basin

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to Colorado and the Colorado River Basin of the United States.

Hidalgo *et al*. (2000) used a new form of principal components analysis to reconstruct a history of streamflow for the Upper Colorado River Basin based on information obtained from tree-ring data, after which they compared their results to those of Stockton and Jacoby (1976). They found the two approaches yielded similar results, except Hidalgo *et al*.'s approach responded with more intensity to periods of below-average streamflow or regional drought. Thus it was easier for them to determine there has been "a near-centennial return period of extreme drought events in this region," going back to the early 1500s.

Woodhouse *et al*. (2006) also generated proxy reconstructions of water-year streamflow for the Upper Colorado River Basin, based on four key gauges (Green River at Green River, Utah; Colorado River near Cisco, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona) and using an expanded tree-ring network and longer calibration records than in previous efforts. They found the major drought of 2000–2004, "as measured by 5-year running means of water-year total flow at Lees Ferry ... is not without precedence in the tree ring record" and "average reconstructed annual flow for the period 1844–1848 was lower." They reported "two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004," and six other periods "have a 10% or greater chance of being drier." In addition, their work revealed "longer duration droughts have occurred in the past" and "the Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906–1995 average."

"Overall," the three researchers observed, "these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate." Woodhouse *et al*. concluded "droughts more severe than any 20th to 21st century event occurred in the past," a finding entirely contrary to the climate model projection that global warming promotes longer-lasting droughts of greater severity. The real-world record of Upper Colorado River Basin droughts instead suggests such climatic conditions are more strongly associated with the much colder temperatures that characterized the Little Ice Age.

Woodhouse and Lukas (2006) developed "a network of 14 annual streamflow reconstructions, 300–600 years long, for gages in the Upper Colorado and South Platte River basins in Colorado generated from new and existing tree-ring chronologies." Their expanded streamflow reconstructions indicated "the 20th century gage record does not fully represent the range of streamflow characteristics seen in the prior two to five centuries." The scientists reported "multi-year drought events more severe than the 1950s drought have occurred" and "the greatest frequency of extreme low flow events occurred in the 19th century," with a "clustering of extreme event years in the 1840s and 1850s."

Meko *et al*. (2007) used a newly developed network of tree-ring sites located within the Upper Colorado River Basin, consisting of tree-ring samples from living trees augmented by similar samples obtained from logs and dead standing trees (remnant wood), to extend the record of reconstructed annual flows of the Colorado River at Lees Ferry, Arizona, into the Medieval Warm Period, during which they say "epic droughts are hypothesized from other paleoclimatic evidence to have affected various parts of western North America."

"The most prominent feature of the smoothed long-term reconstruction," Meko *et al*. write, "is the major period of low flow in the mid-1100s," which "25-year running mean occurred in AD 1130–1154." For this level of smoothing, they reported, "conditions in the mid-1100s in the UCRB were even drier than during the extremely widespread late-1500s North American mega-drought (e.g., Stahle *et al*., 2000)." For comparison, they observed "if 'normal' is defined as the observed mean annual flow for 1906–2004, the anomalous flow for AD 1130–1154 was less than 84% of normal," whereas "the lowest 25-year mean of observed flows (1953–1977) was 87% of normal." The authors further noted the 80% confidence band of their data "suggests a greater than 10% probability that the true mean for AD 1130–1154 was as low as 79% of normal." Additionally, the seven scientists reported "a detailed view of the time series of annual reconstructed flow reveals that the mid-1100s is characterized by a series of multi-year low-flow pluses imbedded in a generally dry 62-year period (1118–1179)," and "the key drought signature is a stretch of 13 consecutive years of below normal flow (1143–1155)." They also noted "in no other period of the reconstruction was flow below normal for more than 10 consecutive years, and the longest stretch of consecutive dry years in the reconstruction for the modern instrumental period (post 1905) was just 5 years."

Gray *et al*. (2011) observed "over the past decade severe drought conditions in the western United States have driven a growing interest in the range of natural hydrologic variability that has occurred over past centuries to millennia," as have "concerns related to the detection and prediction of anthropogenic climate-change impacts." The authors noted in order to know how unusual or unprecedented certain aspects of climate may have been recently, one must know how they varied over past centuries to millennia, when man's influence on them was minimal or non-existent. Against this backdrop, the three U.S. researchers derived millennial-length records of water year (October–September) streamflow for three key Upper Colorado River tributaries—the White, Yampa, and Little Snake Rivers—based on tree-ring data they obtained from 75 preexistent chronologies for sites scattered throughout the region, where each chronology was derived from average annual ring-widths of at least 15 and as many as 80 trees per site.

They found "as in previous studies focused on the Upper Colorado River system as a whole (e.g., Meko *et al*., 2007)," the sub-basin reconstructions "show severe drought years and extended dry periods well outside the range of observed flows." Although they noted 1902 and 2002 "were among the most severe in the last ~1,000 years," they found "pre-instrumental dry events often lasted a decade or longer with some extended low-flow regimes persisting for 30 years or more." In addition, their research "shows anomalous wetness in the 20th century, a finding that has been well documented in the Colorado River basin and surrounding areas (Gray *et al*., 2004, 2007; Woodhouse *et al*., 2006; Watson *et al*., 2009)."

In an additional study from the Colorado Plateau region with implications for drought in the entire western United States, Routson *et al*. (2011) reported "many southwestern United States high-resolution proxy records show numerous droughts over the past millennium, including droughts far more severe than we have experienced during the historical period (e.g., Woodhouse and Overpeck, 1998; Cook *et al*., 2004, 2010; Meko *et al*., 2007)." They observed "the medieval interval (ca. AD 900 to 1400), a period with relatively warm Northern Hemisphere temperatures, has been highlighted as a period in western North America with increased drought severity, duration and extent (e.g., Stine, 1994; Cook *et al*., 2004, 2010; Meko *et al*., 2007; Woodhouse *et al*., 2010)," and "the mid-12th century drought associated with dramatic decreases in Colorado River flow (Meko *et al*., 2007), and the 'Great Drought' associated with the abandonment of Ancient Pueblo civilization in the Colorado Plateau region (Douglass, 1929), all occurred during the medieval period." These observations suggest significant Northern Hemispheric warmth tends to produce western North America megadroughts.

Routson *et al*. used a new tree-ring record derived from living and remnant bristlecone pine wood from the headwaters region of the Rio Grande River in Colorado (USA), along with other regional records, to evaluate "periods of unusually severe drought over the past two millennia (268 BC to AD 2009)." The three researchers reported their work "reveals two periods of enhanced drought frequency and severity relative to the rest of the record," and "the later period, AD ~1050–1330, corresponds with medieval aridity well documented in other records." The researchers reported "the earlier period is more persistent (AD ~1–400), and includes the most pronounced event in the ... chronology: a multi-decadal-length drought during the 2nd century," which "includes the unsmoothed record's driest 25-year interval (AD 148–173) as well as a longer 51-year period, AD 122–172, that has only two years with ring width slightly above the long-term mean," Also, "the smoothed chronology shows the periods AD 77–282 and AD 301–400 are the longest (206 and 100 years, respectively, below the long-term average) droughts of the entire 2276-year record." They observed this second century drought "impacted a region that extends from southern New Mexico north and west into Idaho."

Routson *et al*. reported "reconstructed Colorado Plateau temperature suggests warmer than average temperature could have influenced both 2nd century and medieval drought severity," and "available data also suggest that the Northern Hemisphere may have been warm during both intervals." Routson *et al*. suggested the southwestern United States could experience similar or even more severe megadroughts in the future, as they suspect it will continue to warm in response to continued anthropogenic CO_2 emissions. If global warming is in fact the major cause of western USA drought, then it must be significantly cooler now than it was during those two prior multicentury warm periods, since we have not yet experienced droughts anywhere near the severity or duration of those that occurred in the Roman and Medieval Warm Periods.

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7.4.4.3.3.6 Arizona/New Mexico

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the Arizona and New Mexico region of the United States.

Ni *et al*. (2002) developed a 1,000-year history of cool-season (November–April) precipitation for each climate division of Arizona and New Mexico from a network of 19 tree-ring chronologies. They determined "sustained dry periods comparable to the 1950s drought" occurred in "the late 1000s, the mid 1100s, 1570–97, 1664–70, the 1740s, the 1770s, and the late 1800s." They also noted the 1950s drought "only lasted from approximately 1950 to 1956," whereas the sixteenth-century megadrought lasted more than four times longer.

Rasmussen *et al*. (2006) derived a record of regional relative moisture from variations in the annual band thickness and mineralogy of two columnar stalagmites collected from Carlsbad Cavern and Hidden Cave in the Guadalupe Mountains near the New Mexico/Texas border. They discovered both records "suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record," confirming the significant droughts and floods of recent times are certainly not unprecedented during the past millennium or more.

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7.4.4.3.3.7 Multiple States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to multiple-state regions in the western United States.

Several studies have examined historical drought trends across multiple states in the western United States. Gray *et al*. (2003), for example, examined 15 tree ring-width chronologies used in previous reconstructions of drought for evidence of low-frequency variations in five regional composite precipitation histories in the central and southern Rocky Mountains. They found "strong multidecadal phasing of moisture variation was present in all regions during the late 16th-century megadrought," and "oscillatory modes in the 30–70 year domain persisted until the mid-19th century in two regions, and wet-dry cycles were apparently synchronous at some sites until the 1950s drought." They speculated "severe drought conditions across consecutive seasons and years in the central and southern Rockies may ensue from coupling of the cold phase Pacific Decadal Oscillation with the warm phase Atlantic Multidecadal Oscillation," which they envisioned as having happened in both the severe 1950s drought and the late sixteenth-century megadrought. This suggests episodes of extreme dryness in this part of the country may be driven in part by naturally recurring climate "regime shifts" in the Pacific and Atlantic Oceans.

Seager (2007) also suggested ocean oscillations might bear a good deal of the blame for large-scale drought in the western United States. Seager studied the global context of the drought that affected nearly the entire United States, northern Mexico, and the Canadian Prairies—but most particularly the American West—between 1998 and 2004. Based on atmospheric reanalysis data and ensembles of climate model simulations forced by global or tropical Pacific sea surface temperatures over the period January 1856 to April 2005, Seager compared the climatic circumstances of the recent drought with those of the five prior great droughts of North America: the Civil War drought of 1856–1865, the 1870s drought, the 1890s drought, the great Dust Bowl drought, and the 1950s drought. Seager reported the 1998–2002 period of the recent drought "was most likely caused by multiyear variability of the tropical Pacific Ocean," noting the recent drought "was the latest in a series of six persistent global hydroclimate regimes, involving a persistent La Niña-like state in the tropical Pacific and dry conditions across the midlatitudes of each hemisphere."

No aspect of Seager's study implicated global warming, either CO_2-induced or otherwise, as a cause of or contributor to the turn-of-the-twentieth-century drought that affected large portions of North America. Seager noted, for example, "although the Indian Ocean has steadily warmed over the last half century, this is not implicated as a cause of the turn of the century North American drought because the five prior droughts were associated with cool Indian Ocean sea surface temperatures." In addition, the five earlier great droughts occurred during periods when the mean global temperature was significantly cooler than what it was during the last great drought.

Woodhouse (2004) covered the western United States, reporting what is known about natural hydroclimatic variability throughout the region. Woodhouse described several major droughts that occurred there during the past three millennia, all but the last century of which had atmospheric CO_2 concentrations that never varied by more than about 10 ppm from a mean value of 280 ppm.

For comparative purposes, Woodhouse began by noting "the most extensive U.S. droughts in the 20th century were the 1930s Dust Bowl and the 1950s droughts." The first of these droughts lasted "most of the decade of the 1930s" and "occurred in several waves," while the latter "also occurred in several waves over the years 1951–1956." Far more severe than either of these two droughts was the sixteenth century megadrought, which lasted from 1580 to 1600 and included northwestern Mexico in addition to the southwestern United States and the western Great Plains. There was also The Great Drought, which spanned the last quarter of the thirteenth century and was actually the last in a series of three thirteenth-century droughts, the first of which may have been even more severe than the last. In addition, Woodhouse noted there was a period of remarkably sustained drought in the second half of the twelfth century.

According to Woodhouse, "the 20th century climate record contains only a subset of the range of natural climate variability in centuries-long and longer paleoclimatic records." This subset does not even begin to approach the level of drought severity and duration experienced in prior centuries and millennia, which fact was confirmed in a separate paper published by Woodhouse with four coauthors six years later (Woodhouse *et al*., 2010). It would take a drought much more extreme than the most extreme droughts of the twentieth century to propel the western United States and adjacent portions of Canada and Mexico into a truly unprecedented state of dryness.

Benson *et al*. (2007) reviewed and discussed the possible impacts of early-eleventh, middle-twelfth, and late-thirteenth century droughts on three Native American cultures that occupied parts of the western United States (Anasazi, Fremont, Lovelock) plus another culture that occupied parts of southwestern Illinois (Cahokia). According to the authors, "population declines among the various Native American cultures were documented to have occurred either in the early-11th, middle-12th, or late-13th centuries"—AD 990–1060, 1135–1170, and 1276–1297, respectively—and "really extensive droughts impacted the regions occupied by these prehistoric Native Americans during one or more of these three time periods." In particular, they found the middle-twelfth century drought "had the strongest impact on the Anasazi and Mississippian Cahokia cultures," noting "by AD 1150, the Anasazi had abandoned 85% of their great houses in the Four Corners region and most of their village sites, and the Cahokians had abandoned one or more of their agricultural support centers, including the large Richland farming complex." In addition, "the sedentary Fremont appear to have abandoned many of their southern area habitation sites in the greater Uinta Basin area by AD 1150 as well as the eastern Great Basin and the Southern Colorado Plateau," so "in some sense, the 13th century drought may simply have 'finished off' some cultures that were already in decline." Benson *et al*. found these "major reductions in prehistoric Native American habitation sites/population" occurred during a period of "anomalously warm" climatic conditions, which characterized the Medieval Warm Period throughout much of the world at that time.

Two papers by E.R. Cook provide additional information relevant to western United States drought trends. In the first, Cook *et al*. (2004) developed a 1,200-year history of drought for the western half of the country and adjacent parts of Canada and Mexico (hereafter the "West"), based on annually resolved tree-ring records of summer-season Palmer Drought Severity Index derived for 103 points on a 2.5° x 2.5° grid, 68 of which grid points (66% of them) possessed data extending back to AD 800. This reconstruction revealed "some remarkable earlier increases in aridity that dwarf the comparatively short-duration current drought in the 'West.'" Specifically, they reported "the four driest epochs, centered on AD 936, 1034, 1150 and 1253, all occur during a ~400 year interval of overall elevated aridity from AD 900 to 1300," which they observed was "broadly consistent with the Medieval Warm Period."

Commenting on the strength and severity of Medieval drought, the five scientists reported "the overall coincidence between our megadrought epoch and the Medieval Warm Period suggests that anomalously warm climate conditions during that time may have contributed to the development of more frequent and persistent droughts in the 'West,'" as well as the megadrought Rein *et al*. (2004) discovered to have occurred in Peru at about the same time (AD 800–1250). After citing nine other studies providing independent evidence of drought during this time period for various sub-regions of the West, Cook *et al*. warned "any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America" and "future droughts in the 'West' of similar duration to those seen prior to AD 1300 would be disastrous."

It is important to note such an unfortunate fate could befall the western United States even in the absence of CO_2-induced global warming, for the millennial-scale oscillation of climate that brought the world the Medieval Warm Period (which was not CO_2-induced) could be repeating itself during the possibly still-ongoing development of the Current Warm Period. In addition, if the association between global warmth and drought in the western United States is indeed robust, current world temperatures must still be far below those experienced during large segments of the Medieval Warm Period, as no drought of Medieval magnitude has accompanied the modern rise in temperature.

In the second of the two papers, Cook *et al*. (2010) wrote "IPCC Assessment Report 4 model projections suggest that the subtropical dry zones of the world will both dry and expand poleward in the future due to greenhouse warming," and "the US southwest is particularly vulnerable in this regard and model projections indicate a progressive drying there out to the end of the 21st century." They observed "the USA has been in a state of drought over much of the West for about 10 years now," and "while severe, this turn of the century drought has not yet clearly exceeded the severity of two exceptional droughts in the 20th century." As a result, "while the coincidence between the turn of the century drought and projected drying in the Southwest is cause for concern, it is premature to claim that the model projections are correct."

This fact is understood when the "turn of the century drought" is compared with the two "exceptional droughts" that preceded it by a few decades. Based on gridded instrumental Palmer Drought Severity indices for tree-ring reconstruction extending back to 1900, Cook *et al*. (2010) calculated the turn-of-the-century drought had its greatest Drought Area Index value of 59% in the year 2002, whereas the Great Plains/Southwest drought covered 62% of the United States in its peak year of 1954 and the Dust Bowl drought covered 77% of the nation in 1934. In terms of drought duration, on the other hand, things are not quite as clear. Stahle *et al*. (2007) estimated the first two droughts lasted for 12 and 14 years, respectively; Seager *et al*. (2005) estimated them to have lasted for eight and 10 years; and Andreadis *et al*. (2005) estimated them to have lasted for seven and eight years. This yields means of nine and 11 years for the two exceptional droughts, compared with 10 or so years for the turn-of-the-century drought, which makes the latter drought not unprecedented even in the twentieth century.

A comparison of the turn-of-the-century drought with droughts of the prior millennium provides clarity on the topic. Cook *et al*. (2010) noted "perhaps the most famous example is the 'Great Drouth' (sic) of AD 1276–1299 described by A.E. Douglass (1929, 1935)." This 24-year drought was eclipsed by the 38-year drought found by Weakley (1965) to have occurred in Nebraska from AD 1276 to 1313, which the authors say "may have been a more prolonged northerly extension of the 'Great Drouth.'" Even these multidecade droughts pale in comparison to the "two extraordinary droughts discovered by Stine (1994) in California that lasted more than two centuries before AD 1112 and more than 140 years before AD 1350." Each of these megadroughts, as Cook *et al*. (2010) described them, occurred "in the so-called Medieval Warm Period." And they report "all of this happened *prior to the strong greenhouse gas warming that began with the Industrial Revolution* [emphasis in original]."

Given the above-referenced medieval megadroughts "occurred without any need for enhanced radiative forcing due to anthropogenic greenhouse gas forcing"—because there was none at that time—Cook *et al*. (2010) concluded "there is no guarantee that the response of the climate system to greenhouse gas forcing will result in megadroughts of the kind experienced by North America in the past." Those who continue to claim global warming will trigger medieval-like megadroughts also must acknowledge the Medieval Warm Period of a thousand years ago had to have been much warmer than the Current Warm Period has been to date.

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7.4.4.3.4 Southern

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the southern United States.

Writing as background for their study, Chen *et al*. (2012) reported "the IPCC (2007) and the U.S. Climate Report (Karl *et al*., 2009) predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water," with the forecast result "it is likely that drought intensity, frequency, and duration will increase in the future for the Southern United States." To test the validity of this claim, Chen *et al*. used the standard precipitation index (SPI) to characterize drought intensity and duration throughout the Southern United States (SUS) over the past century.

According to the nine researchers, the results indicated there were "no obvious increases in drought duration and intensity during 1895–2007." Instead, they found "a slight (not significant) decreasing trend in drought intensity." They noted "although reports from IPCC (2007) and the U.S. Climate Report (Karl *et al*., 2009) indicated that it is likely that drought intensity, frequency, and duration will increase in the future for the SUS, we did not find this trend in the historical data." They also noted, although "the IPCC (2007) and U.S. Climate Report predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water," they "found no obvious increase in air temperature for the entire SUS during 1895–2007."

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7.4.4.3.5 Entire Conterminous United States

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the conterminous United States.

Andreadis and Lettenmaier (2006) examined twentieth-century trends in soil moisture, runoff, and drought over the conterminous United States with a hydroclimatological model forced by real-world measurements of precipitation, air temperature, and wind speed over the period 1915–2003. This work revealed "droughts have, for the most part, become shorter, less frequent, less severe, and cover a smaller portion of the country over the last century."

Using the self-calibrating Palmer (1965) drought severity index (SCPDSI), as described by Wells *et al*. (2004), Van der Schrier *et al*. (2006) constructed maps of summer moisture availability across a large portion of North America (20–50°N, 130–60°W) for the period 1901–2002 with a spatial latitude/longitude resolution of 0.5° x 0.5°. This revealed for the area as a whole, "the 1930s and 1950s stand out as times of persistent and exceptionally dry conditions, whereas the 1970s and the 1990s were generally wet." The authors reported "no statistically significant trend was found in the mean summer SCPDSI over the 1901–2002 period, nor in the area percentage with moderate or severe moisture excess or deficit." Moreover, they could not find a single coherent area within the SCPDSI maps that "showed a statistically significant trend over the 1901–2002 period."

Fye *et al*. (2003) developed gridded reconstructions of the summer (June–August) basic Palmer Drought Severity Index over the continental United States, based on "annual proxies of drought and wetness provided by 426 climatically sensitive tree-ring chronologies." This work revealed the greatest twentieth century moisture anomalies across the United States were the 13-year pluvial in the West in the early part of the century and the epic droughts of the 1930s (the Dust Bowl years) and 1950s, which lasted 12 and 11 years, respectively. Comparing these events to earlier wet and dry periods, they made the following points.

The 13-year pluvial from 1905 to 1917 had three earlier analogs: an extended 16-year pluvial from 1825 to 1840, a prolonged 21-year wet period from 1602 to 1622, and a 10-year pluvial from 1549 to 1558. The 11-year drought from 1946 to 1956, on the other hand, had at least 12 earlier analogs in terms of location, intensity, and duration, but the Dust Bowl drought was greater than all of them—except for a sixteenth century "megadrought" that lasted some 18 years and was, in the words of Fye *et al*., "the most severe sustained drought to impact North America in the past 500 to perhaps 1000 years."

Stahle *et al*. (2000) developed a long-term history of North American drought from reconstructions of the Palmer Drought Severity Index based on analyses of many lengthy tree-ring records. This history also showed the 1930s Dust Bowl drought in the United States was eclipsed by the sixteenth century megadrought. This incredible period of dryness, as they described it, persisted "from the 1540s to 1580s in Mexico, from the 1550s to 1590s over the [U.S.] Southwest, and from the 1570s to 1600s over Wyoming and Montana." In addition, it "extended across most of the continental United States during the 1560s," and it recurred with greater intensity over the Southeast during the 1580s to 1590s. Stahle *et al*. reported "the 'megadrought' of the 16th century far exceeded any drought of the 20th century." A "precipitation reconstruction for western New Mexico suggests that the 16th-century drought was the most extreme prolonged drought in the past 2000 years."

Herweijer *et al*. (2006) noted "drought is a recurring major natural hazard that has dogged civilizations through time and remains the 'world's costliest natural disaster.'" With respect to the twentieth century, for example, they reported the "major long-lasting droughts of the 1930s and 1950s covered large areas of the interior and southern states and have long served as paradigms for the social and economic cost of sustained drought in the USA." They also noted "these events are not unique to the twentieth century." They described three periods of widespread and persistent drought in the latter half of the nineteenth century—1856–1865 (the "Civil War" drought), 1870–1877, and 1890–1896—based on evidence obtained from proxy, historical, and instrumental data.

With respect to the first of these mid- to late-nineteenth century droughts, Herweijer *et al*. found it "is likely to have had a profound ecological and cultural impact on the interior USA, with the persistence and severity of drought conditions in the Plains surpassing those of the infamous 1930s Dust Bowl drought." In addition, they reported "drought conditions during the Civil War, 1870s and 1890s droughts were not restricted to the summer months, but existed year round, with a large signal in the winter and spring months."

The three researchers cited the work of Cook and Krusic (2004), who constructed a North American Drought Atlas using hundreds of tree-ring records. This atlas revealed what Herweijer *et al*. described as "a 'Mediaeval Megadrought' that occurred from AD 900 to AD 1300," along with "an abrupt shift to wetter conditions after AD 1300, coinciding with the 'Little Ice Age', a time of globally cooler temperatures" that ultimately gave way to "a return to more drought-prone conditions beginning in the nineteenth century."

The broad picture emerging from the work of Herweijer *et al*. is one where the most severe North American droughts of the past millennium were associated with the globally warmer temperatures of the Medieval Warm Period plus the initial stage of the globally warmer Current Warm Period. Superimposed upon this low-frequency behavior, Herweijer *et al*. found evidence for a "linkage between a colder eastern equatorial Pacific and persistent North American drought over the last 1000 years," further noting "Rosby wave propagation from the cooler equatorial Pacific amplifies dry conditions over the USA." In addition, after using "published coral data for the last millennium to reconstruct a NINO 3.4 history," they applied "the modern-day relationship between NINO 3.4 and North American drought ... to recreate two of the severest Mediaeval 'drought epochs' in the western USA."

How is it that simultaneous global-scale warmth and regional-scale cold combine to produce the most severe North American droughts? One possible element is variable solar activity, which, as suggested in Chapter 3 of this report, drives the millennial-scale oscillation of climate that produced the global Medieval Warm Period, Little Ice Age, and Current Warm Period. When solar activity is in an ascending mode, the globe as a whole warms, but at the same time, to quote from Herweijer *et al*.'s concluding sentence, increased irradiance typically "corresponds to a colder eastern equatorial Pacific and, by extension, increased drought occurrence in North America and other mid-latitude continental regions."

These observations imply the most severe North American droughts should occur during major multi-centennial global warm periods, as has been observed to be the case. Since the greatest such droughts of the Current Warm Period have not approached the severity of those that occurred during the Medieval Warm Period, one might logically infer the global temperature of the Current Warm Period is not as high as the global temperature that prevailed throughout the Medieval Warm Period.

Stahle *et al*. (2007) used "an expanded grid of tree-ring reconstructions of the summer Palmer drought severity indices (PDSI; Cook *et al*., 2004) covering the United States, southern Canada, and most of Mexico to examine the timing, intensity, and spatial distribution of decadal to multidecadal moisture regimes over North America" since AD 1300. In discussing the Current Warm Period, Stahle *et al*. observed, "the Dust Bowl drought of the 1930s and the Southwestern drought of the 1950s were the two most intense and prolonged droughts to impact North America," citing the studies of Worster (1979), Diaz (1983), and Fye *et al*. (2003). During the Little Ice Age, by contrast, Stahle *et al*. found three megadroughts, which they defined as "very large-scale drought[s] more severe and sustained than any witnessed during the period of instrumental weather observations (e.g., Stahle *et al*., 2000)." They reported "much stronger and more persistent droughts have been reconstructed with tree rings and other proxies over North America during the Medieval era (e.g., Stine, 1994; Laird *et al*., 2003; Cook *et al*., 2004)." These latter megadroughts were so impactful Stahle *et al*. referred to them as "no-analog Medieval mega-droughts."

Herweijer *et al*. (2007) used Palmer Drought Severity Index data found in the North American Drought Atlas prepared by Cook and Krusic (2004), derived from a network of drought-sensitive tree-ring chronologies (some stretching back to AD 800 and encompassing the Medieval Warm Period), placing into a longer perspective "the famous droughts of the instrumental record (i.e., the 1930s Dust Bowl and the 1950s Southwest droughts)." They reported, "the famous droughts of the instrumental era are dwarfed by the successive occurrence of multidecade-long 'megadroughts' in the period of elevated aridity between the eleventh and fourteenth centuries AD." They noted medieval megadroughts, although more extreme in terms of persistence, "share the severity and spatial distribution characteristics of their modern-day counterparts." This led them to conclude the mechanism responsible for major North American droughts of the twentieth century "is synonymous with that underlying the megadroughts of the medieval period," the only difference being the degree of persistence of the forcing that caused them.

What, then, is the common denominator shared by the major North American droughts of the modern and medieval periods?

"With ENSO showing a pronounced signal in the gridded drought reconstructions of the last millennium, both in terms of its link to the leading spatial mode, and the leading time scales of drought variability," Herweijer *et al*. concluded "medieval megadroughts were forced by protracted La Niña-like tropical Pacific sea surface temperatures." In addition, they demonstrated "a global hydroclimatic 'footprint' of the medieval era revealed by existing paleoclimatic archives from the tropical Pacific and ENSO-sensitive tropical and extratropical land regions." They observed "this global pattern matches that observed for modern-day persistent North American drought," namely, "a La Niña-like tropical Pacific."

A number of paleoclimate studies demonstrate when Earth was significantly warmer than the present, such as during the Medieval Warm Period, ENSO events were often substantially reduced and sometimes even absent (see Chapter 4). Consequently, since the North American droughts of the Medieval Warm Period dwarfed those of the Current Warm Period—with both produced by La Niña-like conditions (which are more prevalent during times of greater warmth)—it follows that the Medieval Warm Period was significantly warmer than the Current Warm Period.

Climate models typically project CO_2-induced global warming will result in more severe droughts. The much more severe and sustained megadroughts of the Little Ice Age appear to render this claim dubious.

Although the severe and sustained no-analogue megadroughts of the Medieval Warm Period would appear to bolster the climate models' projections, the substantially more severe droughts of that period—if they were indeed related to high global air temperatures—would suggest it is not nearly as warm today as it was during the Medieval Warm Period, when there was far less CO_2 in the air than there is today. These observations undercut the more fundamental claim that the historical rise in the air's

CO_2 content has been responsible for what the IPCC and others have described as unprecedented twentieth century global warming.

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7.4.5 Central and South America

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the regions of Central and South America.

Webster *et al*. (2007) removed an active stalagmite (MC01) from the entrance chamber of Macal Chasm—a cave on the Vaca Plateau west of the Rio Macal in the Cavo District of Belize near the border with Guatemala (~17°N, 89°W)—from which they obtained "reliably dated reflectance, color, luminescence, and C and O stable isotope records for the period from 1225 BC to the present." Upon examination of the record, the authors report the interval "from AD 750 to 1150 was the most prolonged dry phase in our 3300-year record." This time period corresponds well with the MWP's mean time of occurrence around the globe, which, Webster *et al*. observed, "coincided with the collapse of the Maya civilization." They observed their data depicted "a series of droughts centered at about AD 780, 910, 1074, and 1139," with "successive droughts increasing in severity."

The seven scientists reported the results of their investigations "add to a growing body of evidence suggesting that severe dryness affected a broad region of Mesoamerica and contributed to the collapse of the Maya civilization during the Late Classic period." Consequently, although the warmth of the MWP benefited Norse settlers on Greenland, its dryness across a broad swath of Mesoamerica spelled an end to the indigenous civilization of that region.

Morengo (2009) worked with hydro-meteorological indices for the Amazon basin and its several sub-basins "to explore long-term variability of climate since the late 1920s and the presence of trends and/or cycles in rainfall and river indices in the basin." These analyses were based on northern and southern Amazonian rainfall data originally developed by Marengo (1992) and Marengo and Hastenrath (1993), and subsequently updated by Marengo (2004). According to the Brazilian researcher, "no systematic unidirectional long-term trends towards drier or wetter conditions [were] identified." Instead, he found "the rainfall and river series show variability at inter-annual scales." Of the patterns he uncovered, Morengo observed they are "characteristic of decadal and multi-decadal modes," which he describes as "indicators of natural climate variability" linked to the El Niño/Southern Oscillation, "rather than any unidirectional trend towards drier conditions (as one would expect, due to increased deforestation or to global warming)."

Minetti *et al*. (2010) evaluated the annual occurrence of droughts and their persistence in what they described as "an attempt to determine any aspects of the impact of global warming." They examined a regional inventory of monthly droughts for the portion of South America located south of approximately 22°S latitude, dividing the area of study into six sections (the central region of Chile plus five sections making up most of Argentina).

They identified "the presence of long favorable tendencies [1901–2000] regarding precipitations or the inverse of droughts occurrence are confirmed for the eastern Andes Mountains in Argentina with its five sub-regions (Northwest Argentina, Northeast Argentina, Humid Pampa, West-Centre Provinces and Patagonia) and the inverse over the central region of Chile." From the middle of 2003 to 2009, however, they reported "an upward trend in the occurrence of droughts with a slight moderation over the year 2006." They additionally noted the driest single-year periods were 1910–1911, 1915–1916, 1916–1917, 1924–1925, and 1933–1934, suggesting twentieth century global warming has not promoted an abnormal increase in droughts in the southern third of South America.

Mundo *et al*. (2012) employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of Argentina's Neuquen River over the 654-year period AD 1346–2000. According to the eight researchers, in terms of the frequency, intensity, and duration of droughts and pluvial events, "the 20th century contains some of the driest and wettest annual to decadal-scale events in the last 654 years." They also noted "longer and more severe events were recorded in previous centuries." Importantly, the bulk of the 554 years preceding the twentieth century were part of the much colder Little Ice Age, and it would thus appear the global warming of the past century has brought Argentina's Neuquen River less extreme streamflow conditions.

Masiokas *et al*. (2012) developed the first reconstruction and quantitative analysis of variations in snow accumulation for the past eight-and-a-half centuries in the Andes between 30° and 37°S. The record was based on "instrumental rainfall and streamflow data from adjacent lowlands, a variety of documentary records, and century-long tree-ring series of precipitation-sensitive species from the western side of the Andes," representing "the first attempt to reconstruct annually-resolved, serially complete snowpack variations spanning most of the past millennium in the Southern Hemisphere." This record "allows testing the relative severity of recent 'extreme' conditions in a substantially longer context."

The eight researchers report "variations observed in the last 60 years are not particularly anomalous when assessed in a multi-century context," noting both extreme high and low snowpack values "have not been unusual when assessed in the context of the past eight centuries." They found "the most extreme dry decades are concentrated between the late 16th century and the mid-18th century," and there were "decade-long periods of high snowpack levels that equaled or probably surpassed those recorded during the past six decades."

The results of the several studies described above indicate the warming of the twentieth and early twenty-first centuries has brought nothing unusual, unnatural, or unprecedented in the way of trends in drought frequency and severity for the studied areas of South America.

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7.4.6 Global

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting droughts. This subsection highlights such research as it pertains to the entire planet.

Svensson *et al*. (2005) examined twentieth century river flow data for a group of 21 stations distributed around the globe, which they obtained from the Global Runoff Data Centre in Koblenz, Germany. Individual record lengths for the 21 stations varied from 44 to 100 years, with an average of 68 years, and the three researchers' analyses of the data consisted of computing trends in both high flows and low flows using Mann-Kendall and linear regression methods. In the case of high flows, their work revealed slightly more stations exhibiting significant negative trends (reduced flooding) than significant positive trends (increased flooding). With respect to low flows, nearly all stations showed increasing trends, approximately half of which were significant at the 90% level, indicative of a general trend of decreasing drought throughout the world.

Huntington (2006) reviewed the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and a number of other water-related parameters. He found on a globally averaged basis, "precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al*., 1997; Hulme *et al*., 1998)." He also reported "an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987)," and a reanalysis of those trends for the period 1920–1995 "confirmed an increase in world continental runoff during the 20th century (Labat *et al*., 2004)." Huntington further reported "summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al*., 2000)."

Narisma *et al*. (2007) analyzed "global historical rainfall observations to detect regions that have undergone large, sudden decreases in rainfall [that] are statistically significant at the 99% level, are persistent for at least ten years, and ... have magnitudes that are [mostly] 10% lower than the climatological normal (1901–2000 rainfall average)." Working with the gridded high-resolution (0.5 x 0.5 degrees of latitude and longitude) global precipitation dataset of Mitchell *et al*. (2004), which covers the period 1901–2000, they identified 30 drought episodes throughout the world that satisfied these stringent criteria during the twentieth century. These episodes included the sudden and prolonged Sahel drought of Africa in the late 1960s; the United States Dust Bowl of the 1930s and Southwest drought of the 1950s (which also affected parts of Mexico); the strong and persistent droughts that occurred in northeast China in the 1920s, in Kazakhstan and regions of the former Soviet Union in the late 1930s, in southeast Australia in the late 1930s, and in southern Africa and eastern Europe in the 1980s; the World War II droughts of 1937–1945; and the droughts that occurred over large regions of East India and Bangladesh in the 1950s.

Seven of the 30 severe and persistent droughts identified by Narisma *et al*. occurred during the first two decades of the twentieth century (1901–1920), seven occurred during the next two decades (1921–1940), eight during the middle two decades of the century (1941–1960), only five during the next two decades (1961–1980), and a mere three during the final two decades of the century (1981–2000). This distribution is not at all what one would have expected if the model-based thesis propounded by the

IPCC were correct.

The scientists who performed the analysis reported the 30 major droughts they identified were "mostly located in semi-arid and arid regions" that "are naturally prone to large fluctuations." The 30 major droughts of the twentieth century were therefore likely natural in all respects and hence "indicative of what could also happen in the future," as Narisma *et al*. state in their concluding paragraph.

Sheffield and Wood (2008) studied "variability and trends in soil moisture and drought characteristics, globally and regionally over the second half of the twentieth century." They used "a global soil moisture dataset derived from a model simulation of the terrestrial hydrologic cycle," which was "driven by a hybrid observation-reanalysis-based meteorological dataset." This work revealed "an overall increasing trend in global soil moisture, driven by increasing precipitation, underlies the whole analysis, which is reflected most obviously over the western hemisphere and especially in North America." In addition, they determined "trends in drought characteristics are predominantly decreasing" and "concurrent changes in drought spatial extent are evident, with a global decreasing trend of -0.021% to -0.035% per year." They also discovered "a switch in later years to a drying trend, globally and in many regions," which they say was "concurrent with increasing temperatures." This drying trend was not strong enough to overpower the increasing trend of global soil moisture over the entire half-century of their analysis.

In a subsequent analysis of the same time period, Sheffield *et al*. (2009) used "observation-driven simulations of global terrestrial hydrology and a cluster algorithm that searches for spatially connected regions of soil moisture" to identify "296 large scale drought events (greater than 500,000 km^2 and longer than 3 months) globally for 1950–2000." They reported "the mid-1950s showed the highest drought activity and the mid-1970s to mid-1980s the lowest activity."

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7.5 Floods

Climate model simulations generally predict a future with more frequent and more severe floods in response to CO_2-induced global warming. Confirming such predictions has remained an elusive task, according to the IPCC, which claims in its most recent report "there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods on a global scale" (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

Contrary to the IPCC's assessment of the situation, there exists a large body of scientific research on this topic. According to that research, as outlined in the subsections that follow, there is much evidence to conclude CO_2-induced global warming is not currently increasing the frequency and/or magnitude of floods, nor will it likely impact such phenomena in the future.

7.5.1 Africa

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Africa.

Noting "droughts and floods represent extreme conditions, and are precisely those that are foreseen to increase in [the] future with global change," Heine (2004) analyzed soil sequences and slackwater deposits laid down over the course of the Holocene in valleys of the Namibian Desert, located between southern Angola and South Africa along the South Atlantic Ocean and stretching inland about 200 km, where it abuts on Africa's Great Western Escarpment. The author reports "during the Holocene, slackwater deposits of the Namib Desert valleys accumulated between ca. 10 and 8 ka BP and between ca. 2 and 0 ka BP." Of the latter period, he notes "the youngest accumulation phase occurred during the Little Ice Age (LIA, ca. AD 1300 to 1850)." In addition, he finds "the biggest flash floods of the LIA, in most catchments, experienced water levels in the valleys that exceeded the most extreme floods of the last 100 to 150 years."

Commenting on the nature of the LIA itself, Heine reports "maximum LIA cooling occurred around AD 1700 (ca. -1°C)," noting "this cold period was coeval with cool events recorded in a large variety of proxy data from all sites over southern Africa and from corals in the ocean off southwestern Madagascar (Tyson *et al*., 2001)."

In Africa's Namib Desert, the greatest floods of the past two millennia occurred during its coldest period, the Little Ice Age, with nothing to compare to them during what the IPCC typically describes as the warmest portion of the past two millennia; i.e., the latter part of the twentieth century.

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7.5.2 Asia

As indicated in the introduction of Section 7.5, numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Asia.

Cluis and Laberge (2001) analyzed the flow records of 78 rivers distributed throughout the entire Asia-Pacific region to see if there had been any enhancement of Earth's hydrologic cycle coupled with an increase in variability that might have led to more floods between the mean beginning and end dates of the flow records: 1936 ± 5 years and 1988 ± 1 year, respectively. The two scientists determined mean river discharges were unchanged over this period in 67% of the cases investigated; where they found trends, 69% of them were downward. In addition, maximum river discharges were unchanged in 77% of the cases investigated; where there were trends, 72% of them were downward. Contrary to model-based claims of global warming leading to more frequent and more severe flooding, the two researchers observed no changes in these flood characteristics in the majority of the rivers they studied; and where there were changes, more of them were of the type that typically leads to less flooding and less severe floods.

Kale *et al*. (2003) conducted geomorphic studies of slackwater deposits in the bedrock gorges of the Tapi and Narmada Rivers of central India, assembling long chronologies of large floods of these rivers. They found "since 1727 at least 33 large floods have occurred on the Tapi River and the largest on the river occurred in 1837." With respect to large floods on the Narmada River, they reported at least nine or ten floods between the beginning of the Christian era and AD 400; between AD 400 and 1000 they documented six or seven floods, between 1000 and 1400 about eight or nine floods, and after 1950 three more such floods. On the basis of texture, elevation, and thickness of the flood units, they conclude "the periods AD 400–1000 and post-1950 represent periods of extreme floods."

What do these findings imply about the effects of global warming on central India flood events? The post-1950 period is often claimed by the IPCC to have been the warmest of the past millennium, and it has indeed experienced some extreme floods. However, the flood characteristics of the AD 400–1000 period are described in equivalent terms, and this was a rather cold climatic interval known as the Dark Ages Cold Period (see, for example, McDermott *et al*. (2001) and Andersson *et al*. (2003)). In addition, the most extreme flood in the much shorter record of the Tapi River occurred in 1837, near the beginning of one of the colder periods of the Little Ice Age. There appears to be little correlation between the flood characteristics of the Tapi and Narmada Rivers of central India and the thermal state of the global climate.

Touchan *et al*. (2003) developed two reconstructions of spring (May–June) precipitation from tree-ring width measurements, one of them (1776–1998) based on nine chronologies of *Cedrus libani*, *Juniperus excelsa*, *Pinus brutia,* and *Pinus nigra*, and the other (1339–1998) based on three chronologies of *Juniperus excelsa*. The authors report these reconstructions "show clear evidence of multi-year to decadal variations in spring precipitation," with both wet and dry periods of 1–2 years duration being well distributed throughout the record. In the case of more extreme hydrologic events, they found all of the wettest 5-year periods preceded the industrial revolution, manifesting themselves at times when the air's carbon dioxide content was largely unaffected by anthropogenic CO_2 emissions.

In a study of the Upper Volga and Zapadnaya Dvina Rivers, Panin and Nefedov (2010) documented "the geomorphological and altitudinal positions of [human] occupational layers corresponding to 1224 colonization epochs at 870 archaeological sites in river valleys and lake depressions in southwestern Tver province," identifying "a series of alternating low-water (low levels of seasonal peaks, many-year periods without inundation of flood plains) and high-water (high spring floods, regular inundation of floodplains) intervals of various hierarchical rank." The two researchers report finding "low-water epochs coincide with epochs of relative warming, while high-water epochs [coincide] with cooling epochs," because "during the climate warming epochs, a decrease in duration and severity of winters should have resulted in a drop in snow cover water equivalent by the snowmelt period, a decrease in water discharge and flood stage, and a decrease in seasonal peaks in lake levels." They note "a model of past warming epochs can be the warming in the late 20th century, still continuing now." They also report finding, "in the Middle Ages (1.8–0.3 Ky ago), the conditions were favorable for long-time inhabiting [of] river and lake floodplains, which are subject to inundation nowadays." In addition, their results indicate the period AD 1000–1300 hosted the greatest number of floodplain occupations of the period studied.

Panin and Nefedov state this last period and other "epochs of floodplain occupation by humans in the past can be regarded as hydrological analogues of the situation of the late 20th–early current century," which they say "is forming under the effect of directed climate change." This relationship clearly implies the current level of warmth in the portion of Russia that hosts the Upper Volga and Zapadnaya Dvina Rivers is not yet as great as it was during the AD 1000–1300 portion of the Medieval Warm Period.

Davi *et al*. (2006) developed a reconstruction of streamflow that extended from 1637 to 1997, based on absolutely dated tree-ring-width chronologies from five sampling sites in west-central Mongolia, all of which sites were in or near the Selenge River basin, the largest river in Mongolia. Of the ten wettest five-year periods, only two occurred during the twentieth century (1990–1994 and 1917–1921, the second and eighth wettest of the ten extreme periods, respectively), once again indicative of a propensity for less flooding during the warmest portion of the 360-year period.

Jiang *et al*. (2005) analyzed pertinent historical documents to produce a 1,000-year time series of flood and drought occurrence in the Yangtze Delta of Eastern China (30 to 33°N, 119 to 122°E), whose nearly level plain averages only two to seven meters above sea level across 75% of its area and is vulnerable to flooding and maritime tidal hazards. They found alternating wet and dry episodes occurred throughout the 1,000-year period, with the most rapid and strongest of these fluctuations occurring during the Little Ice Age (1500–1850).

Zhang *et al*. (2007) also developed flood and drought histories of the Yangtze Delta for the past thousand years, "from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports." They then applied "continuous wavelet transform … to detect the periodicity and variability of the flood/drought series." The results were compared with 1,000-year temperature histories of northeastern Tibet and southern Tibet. This work revealed, in the words of the researchers, that "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region." They state, "during AD 1400–1700 [the coldest portion of their record, corresponding to much of the Little Ice Age], the proxy indicators showing the annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred." In contrast, they report "during AD 1000–1400 [the warmest portion of their record, corresponding to much of the Medieval Warm Period], relatively stable changes of climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/drought series in the Yangtze Delta region."

Zhang *et al*. (2009) utilized wavelet analysis on the decadal locust abundance data of Ma (1958) for the AD 950s–1950s, the decadal Yangtze Delta flood and drought frequency data of Jiang *et al*. (2005) for the AD 1000s–1950s, and the decadal mean temperature records of Yang *et al*. (2002) for the AD 950s–1950s, "to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China." The international team of Chinese, French, German, and Norwegian researchers found coolings of 160- to 170-year intervals dominated climatic variability in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events. The six scientists state "global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China," noting these findings "challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects." They say their results are an example of "benign effects of global warming on the regional risk of natural disasters."

Zha *et al*. (2012) conducted a paleohydrological field investigation in the central portion of the Jinghe River, the middle and upper reaches of which are located in a semiarid zone with a monsoonal climate, between Binxian county and Chunhua county of Shaanxi Province. Their analysis revealed five extraordinary palaeoflood events determined to have occurred between 4100 and 4000 years BP; these floods "corresponded exactly with palaeoflood events (4200–4000 yr BP) recorded in the middle reaches of Qishuie River," demonstrating "extraordinary flood events were common during the episode of 4200–4000 yr BP in the middle reaches of the Yellow River."

The four Chinese researchers note "during the mid-Holocene climatic optimum, global climate was warm-humid and the climate system was stable," and during this time, they say, "there were no flood records identified in the middle reaches of the Yellow river," citing the work of Huang *et al*. (2011a,b). Thereafter, however, they report "global climatic cooling events occurred at about 4200 years BP, which was also well recorded by various climatic proxies in China," citing Zhang *et al*. (2004). In addition, they write "the decline of the Neolithic Longshan Culture in the period around 4000 years BP was thought to be linked with the global cooling events," as suggested by the work of Wu *et al*. (2001, 2004, 2005)." These observations led them to conclude, "the extraordinary floods recorded in the middle reaches of the Jinghe River were linked to the global climatic events"—all of which were global cooling events..

In a study focusing on the headwater region of the Sushui River within the Yuncheng Basin in the southeast part of the middle reaches of China's Yellow River, Huang *et al*. (2007) constructed a complete catalog of Holocene overbank flooding events at a watershed scale, based on pedo-sedimentary records of the region's semiarid piedmont alluvial plains, including the color, texture, and structure of the sediment profiles, along with determinations of particle-size distributions, magnetic susceptibilities, and elemental concentrations. This work revealed six major episodes of overbank flooding. The first occurred at the onset of the Holocene, the second immediately before the mid-Holocene Climatic Optimum, and the third in the late stage of the mid-Holocene Climatic Optimum. The last three episodes coincided with "the cold-dry stages during the late Holocene." Speaking of the last of the overbank flooding episodes, they note it "corresponds with the well documented 'Little Ice Age,'" when "climate departed from its long-term average conditions and was unstable, irregular, and disastrous," which is pretty much how the Little Ice Age has been described in many other parts of the world as well.

The findings of these several Asian-based studies provide no support for the claim that global warming leads to more frequent and severe flooding. If anything, they tend to suggest just the opposite.

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7.5.3 Europe

7.5.3.1 France

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to France.

On September 8 and 9, 2002, extreme flooding of the Gardon River in southern France occurred as approximately half an average year's rainfall was received in approximately 20 hours. This flooding claimed the lives of several people and caused much damage to towns and villages situated adjacent to the river's channel. The event elicited much coverage in the press, and in the words of Sheffer *et al*. (2003a), "this flood is now considered by the media and professionals to be 'the largest flood on record,'" which record extends back to 1890.

Coincidentally, Sheffer *et al*. were in the midst of a study of prior floods of the Gardon River when the "big one" hit, and they had data spanning a much longer time period against which to compare its magnitude. Based on that data as presented in their paper, they report "the extraordinary flood of September 2002 was not the largest by any means," noting "similar, and even larger floods have occurred several times in the recent past," with three of the five greatest floods they identified to that point in time occurring over the period AD 1400–1800 during the Little Ice Age. Sheffer *et al*. state, "using a longer time scale than human collective memory, paleoflood studies can put in perspective the occurrences of the extreme floods that hit Europe and other parts of the world during the summer of 2002." That perspective clearly shows even greater floods occurred repeatedly during the Little Ice Age, the coldest period of the current interglacial.

Sheffer *et al*. (2008) analyzed geomorphic, sedimentologic, and hydrologic data associated with both historical and late Holocene floods from two caves and two alcoves of a 1,600-meter-long stretch of the Gardon River, which they hoped would provide a longer and better-defined perspective on the subject. They discovered "at least five floods of a larger magnitude than the 2002 flood occurred over the last 500 years," all of which took place, as they describe it, "during the Little Ice Age." In addition, they note "the Little Ice Age has been related to increased flood frequency in France (Guilbert, 1994; Coeur, 2003; Sheffer, 2003; Sheffer *et al*., 2003a,b; Sheffer, 2005), and in Spain (Benito *et al*., 1996; Barriendos and Martin Vide, 1998; Benito *et al*., 2003; Thorndycraft and Benito, 2006a,b)."

Renard *et al*. (2008) employed four procedures for assessing field significance and regional consistency with respect to trend detection in both high-flow and low-flow hydrological regimes of French rivers, using daily discharge data obtained from 195 gauging stations having a minimum record length of 40 years. They determined "at the scale of the entire country, the search for a generalized change in extreme hydrological events through field significance assessment remained largely inconclusive." At the smaller scale of hydroclimatic regions, they also discovered no significant results for most areas.

Wilhelm *et al*. (2012) note "mountain-river floods triggered by extreme precipitation events can cause substantial human and economic losses (Gaume *et al*., 2009)," and they state "global warming is expected to lead to an increase in the frequency and/or intensity of such events (IPCC, 2007), especially in the Mediterranean region (Giorgi and Lionello, 2008)." They point out "reconstructions of geological records of intense events are an essential tool for extending documentary records beyond existing observational data and thereby building a better understanding of how local and regional flood hazard patterns evolve in response to changes in climate."

Wilhelm *et al*. analyzed the sediments of Lake Allos, a 1-km-long by 700-m-wide high-altitude lake in the French Alps (44°14'N, 6°42'35'E), by means of both seismic survey and lake-bed coring, carrying out numerous grain size, geochemical, and pollen analyses of the sediment cores they obtained in conjunction with a temporal context derived using several radionuclide dating techniques. The 13 French researchers report their investigations revealed the presence of 160 graded sediment layers over the last 1,400 years, and comparisons of the most recent of these layers with records of historic floods suggest the sediment layers are indeed representative of significant floods that were "the result of intense meso-scale precipitation events." Of special interest is their finding of "a low flood frequency during the Medieval Warm Period and more frequent and more intense events during the Little Ice Age," which meshes nicely with the results of an analysis of a Spanish lake sediment archive that allowed Moreno *et al*. (2008) to infer "intense precipitation events occurred more frequently during the Little Ice Age than they did during the Medieval Warm Period."

Wilhelm *et al*. additionally state "the Medieval Warm Period was marked by very low hydrological activity in large rivers such as the Rhone (Arnaud *et al*., 2005; Debret *et al*., 2010), the Moyenne Durance (Miramont *et al*., 1998), and the Tagus (Benito *et al*., 2003), and in mountain streams such as the Taravilla lake inlet (Moreno *et al*., 2008)." Of the Little Ice Age, they write, "research has shown higher flood activity in large rivers in southern Europe, notably in France (Miramont *et al*., 1998; Arnaud *et al*., 2005; Debret *et al*., 2010), Italy (Belotti *et al*., 2004; Giraudi, 2005) and Spain (Benito *et al*., 2003), and in smaller catchments (e.g., in Spain, Moreno *et al*., 2008)."

Wilhelm *et al*. conclude their study shows "sediment sequences from high altitude lakes can provide reliable records of flood-frequency and intensity-patterns related to extreme precipitation events," warning "such information is required to determine the possible impact of the current phase of global warming."

Pirazzoli (2000) analyzed tide-gauge and meteorological data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions and strong surge winds in this region "are becoming less frequent." The data also revealed "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding."

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7.5.3.2 Germany

As indicated in the introduction of Section 7.4, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Germany.

Burger *et al*. (2007) reviewed what is known about flooding in southwest Germany over the past three centuries. According to the six scientists, the extreme flood of the Neckar River in October 1824 was "the largest flood during the last 300 years in most parts of the Neckar catchment." They further note "it was the highest flood ever recorded in most parts of the Neckar catchment and also affected the Upper Rhine, the Mosel and Saar." They report the historical floods of 1845 and 1882 "were among the most extreme floods in the Rhine catchment in the 19th century," which they describe as "catastrophic events." The flood of 1845 "showed a particular impact in the Middle and Lower Rhine and in this region it was higher than the flood of 1824." Two extreme floods occurred in 1882, one at the end of November and another at the end of December. Of the first one, Burger *et al*. say "in Koblenz, where the Mosel flows into the Rhine, the flood of November 1882 was the fourth-highest of the recorded floods, after 1784, 1651 and 1920," with the much-hyped late-twentieth century floods of 1993, 1995, 1998, and 2002 not even meriting a mention.

Czymzik *et al*. (2010) write "assumptions about an increase in extreme flood events due to an intensified hydrological cycle caused by global warming are still under discussion and must be better verified," while noting some historical flood records indicate "flood frequencies were higher during colder periods (Knox, 1993; Glaser and Stangl, 2004), challenging the hypothesis of a correlation between the frequency of extreme floods and a warmer climate."

In June 2007 Czymzik *et al*. retrieved two sediment cores from the deepest part of Lake Ammersee in southern Germany (48°00'N, 11°07'E), which is fed primarily by the River Ammer. They analyzed the cores using what they describe as "a novel methodological approach that combines microfacies analyses, high-resolution element scanning (μ-XRF), stable isotope data from bulk carbonate samples (δ^{13}Ccarb, δ^{18}Ocarb), and X-ray diffraction (XRD) analyses (Brauer *et al*., 2009)." The six scientists determined the flood frequency distribution over the 450-year time series "is not stationary but reveals maxima for colder periods of the Little Ice Age when solar activity was reduced." They report "similar observations have been made in historical flood time series of the River Main, located approximately 200 km north of Ammersee (Glaser and Stangl, 2004), pointing to a wider regional significance of this finding."

Bormann *et al*. (2011) write, "following several severe floods in Germany during the past two decades, [the] mass media as well as scientists have debated the relative contributions of climate and/or anthropogenic processes to those floods." The three researchers utilized long time-series of stage and discharge data obtained from 78 river gauges in Germany, searching for trends in flood frequency, peak discharge, peak stage, and stage-discharge relationships, where all variables investigated had to have a temporal history of at least half a century.

They first established the nature of Germany's temperature history, noting Schonwiese (1999) identified a homogenous positive trend of 0.5–1.0°C over the course of the twentieth century, which was subsequently confirmed by Gerstengarbe and Werner (2008) and Bormann (2010). Then, in terms of land use change between 1951 and 1989, they report "agricultural area in Germany decreased from 57.8% to 53.7%, while forested areas remained almost constant." During this period, they report, "impervious areas increased sharply from 7.4% to 12.3%," and they state "this trend has continued since 1989," with impervious areas further increasing from 11.2% to 13.1%, forest areas increasing from 29.3% to 30.1%, and agricultural area decreasing from 54.7% to 52.5%. As a consequence of the net increase in impervious surfaces, they note, "runoff generation can be expected to increase and infiltration and groundwater recharge decrease," which would be expected to lead to increases in river flow and a potential for more frequent and extreme floods. However, they report "most stations analyzed on the German rivers did not show statistically significant trends in any of the metrics analyzed."

In light of these observations—plus the fact that "most decadal-scale climate-change impacts on flooding (Petrow and Merz, 2009) are small compared to historic peaks in flood occurrence (Mudelsee *et al*., 2006)"—Bormann *et al*. conclude these facts "should be emphasized in the recent discussion on the effect of climate change on flooding." The warming experienced in Germany over the past century has not led to unprecedented flooding; in fact, it has not led to any increase in flooding.

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7.5.3.3 United Kingdom

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to the United Kingdom.

Reynard *et al*. (2001) used a continuous flow simulation model to assess the impacts of potential climate and land use changes on flood regimes of the UK's Thames and Severn Rivers. As is typical of a model study, it predicted modest increases in the magnitudes of 50-year floods on these rivers when the climate was forced to change as predicted for various global warming scenarios. However, when the modelers allowed forest cover to rise concomitantly, they found this land use change "acts in the opposite direction to the climate changes and under some scenarios is large enough to fully compensate for the shifts due to climate."

To better determine what might actually happen in the real world, therefore, it is important to consider how the forested areas of the rivers' catchments might change in the future. Two things come into play here. First, if forests are deemed to be important carbon sinks for which countries may get sequestration credits, and if nations begin to employ them as such, the UK government may promote the development of new forests on much of the land in question. Second, as the air's CO_2 content continues to rise, there will be a great natural impetus for forests to expand their ranges and grow in areas where grasses now dominate the landscape. Consequently, forests may expand on the river catchments and neutralize any predicted increases in flood activity in a future high-CO_2 world.

Macklin *et al*. (2005) developed what they described as "the first probability-based, long-term record of flooding in Europe, which spans the entire Holocene and uses a large and unique database of ^{14}C-dated British flood deposits," They compared their reconstructed flood history "with high-resolution proxy-climate records from the North Atlantic region, northwest Europe and the British Isles to critically test the link between climate change and flooding." They determined "the majority of the largest and most widespread recorded floods in Great Britain [had] occurred during cool, moist periods," and "comparison of the British Holocene palaeoflood series ... with climate reconstructions from tree-ring patterns of subfossil bog oaks in northwest Europe also suggests that a similar relationship between climate and flooding in Great Britain existed during the Holocene, with floods being more frequent and larger during relatively cold, wet periods." In addition, they state "an association between flooding episodes in Great Britain and periods of high or increasing cosmogenic ^{14}C production suggests that centennial-scale solar activity may be a key control of non-random changes in the magnitude and recurrence frequencies of floods."

Noting "recent flood events have led to speculation that climate change is influencing the high-flow regimes of UK catchments," and that "projections suggest that flooding may increase in [the] future as a result of human-induced warming," Hannaford and Marsh (2008) used the UK "benchmark network" of 87 "near-natural catch-ments" identified by Bradford and Marsh (2003) to conduct "a UK-wide appraisal of trends in high-flow regimes unaffected by human disturbances." They report "significant positive trends were observed in all high-flow indicators ... over the 30–40 years prior to 2003, primarily in the maritime-influenced, upland catchments in the north and west of the UK." However, they say "there is little compelling evidence for high-flow trends in lowland areas in the south and east." They also found "in western areas, high-flow indicators are correlated with the North Atlantic Oscillation Index (NAOI)," so "recent trends may therefore reflect an influence of multi-decadal variability related to the NAOI." In addition, they state longer river flow records from five additional catchments they studied "provide little compelling evidence for long-term (>50 year) trends but show evidence of pronounced multi-decadal fluctuations."

Hanaford and Marsh also found "in comparison with other indicators, there were fewer trends in flood magnitude" and "trends in peaks-over-threshold frequency and extended-duration maxima at a gauging station were not necessarily associated with increasing annual maximum instantaneous flow." They conclude "considerable caution should be exercised in extrapolating from any future increases in runoff or high-flow frequency to an increasing vulnerability to extreme flood events."

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7.5.3.4 Spain

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Spain.

"Starting from historical document sources, early instrumental data (basically, rainfall and surface pressure) and the most recent meteorological information," Llasat *et al*. (2005) analyzed "the temporal evolution of floods in NE Spain since the 14th century," focusing on the river Segre in Lleida, the river Llobregat in El Prat, and the river Ter in Girona. The found "an increase of flood events for the periods 1580–1620, 1760–1800 and 1830–1870," and they report "these periods are coherent with chronologies of maximum advance in several alpine glaciers." In addition, calculations from their tabulated data for the aggregate of the three river basins show the mean number of what Llasat *et al*. call catastrophic floods per century for the fourteenth through nineteenth centuries was 3.55 ± 0.22, while the corresponding number for the twentieth century was only 1.33 ± 0.33.

The four Spanish researchers conclude, "we may assert that, having analyzed responses inherent to the Little Ice Age and due to the low occurrence of frequent flood events or events of exceptional magnitude in the 20th century, the latter did not present an excessively problematic scenario." Having introduced their paper with descriptions of the devastating effects of the September 1962 flash flood in Catalonia (more than 800 deaths), the August 1996 flash flood in the Spanish Pyrenees (87 deaths), and the floods of September 1992 that produced much loss of life and material damage in France and Italy, they hastened to add the more recent "damage suffered and a perception of increasing vulnerability is something very much alive in public opinion and in economic balance sheets."

Benito *et al*. (2010) reconstructed flood frequencies of the Upper Guadalentin River in southeast Spain using "geomorphological evidence, combined with one-dimensional hydraulic modeling and supported by records from documentary sources at Lorca in the lower Guadalentin catchment." The combined palaeoflood and documentary records indicate past floods were clustered during particular time periods: AD 950–1200 (10), AD 1648–1672 (10), AD 1769–1802 (9), AD 1830–1840 (6), and AD 1877–1900 (10), where the first time interval coincides with the Medieval Warm Period and the latter four fall within the confines of the Little Ice Age. By calculating mean rates of flood occurrence over each of the five intervals, a value of 0.40 floods per decade during the Medieval Warm Period and an average value of 4.31 floods per decade over the four parts of the Little Ice Age can be determined. The latter value is more than ten times greater than the mean flood frequency experienced during the Medieval Warm Period.

Barredo *et al*. (2012) say "economic impacts from flood disasters have been increasing over recent decades," adding, "despite the fact that the underlying causes of such increase are often attributed to a changing climate, scientific evidence points to increasing exposure and vulnerability as the main factors responsible for the increase in losses," citing the studies of Pielke and Landsea (1998), Crompton and McAneney (2008), Pielke *et al*. (2008), Barredo (2009, 2010), and Neumayer and Barthel (2011). Barredo *et al*. examined "the time history of insured losses from floods in Spain between 1971 and 2008," striving to see "whether any discernible residual signal remains after adjusting the data for the increase in the number and value of insured assets over this period of time."

The "most salient feature" of Barredo *et al*.'s findings, as they describe it, is "the absence of a significant positive trend in the adjusted insured flood losses in Spain," suggesting "the increasing trend in the original losses is explained by socio-economic factors, such as the increases in exposed insured properties, value of exposed assets and insurance penetration." They add "there is no residual signal that remains after adjusting for these factors," so "the analysis rules out a discernible influence of anthropogenic climate change on insured losses," which they say "is consistent with the lack of a positive trend in hydrologic floods in Spain in the last 40 years."

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7.5.3.5 Switzerland

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to Switzerland.

Schmocker-Fackel and Naef (2010a) investigated how flooding in Switzerland may have responded to the post-Little Ice Age warming of the past century and a half, especially in light of the extreme flooding that occurred there in 1999, 2005, and 2007. They "analyzed streamflow data from 83 stations with a record length of up to 105 years, complemented with data from historical floods dating back to 1850." The two researchers found, "in Switzerland, periods with frequent floods have alternated with quieter periods during the last 150 years," and "since 1900, flood-rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa." They also note although "three of the four largest large-scale flood events in northern Switzerland have all occurred within the last ten years," "a similar accumulation of large floods has already been observed in the second half of the 19th century," and "studies about changes in precipitation frequencies in Switzerland come to similar conclusions," citing the work of Bader and Bantle (2004).

In a contemporaneous publication, Schmocker-Fackel and Naef (2010b) collected and analyzed historical flood data from 14 catchments in northern Switzerland. This second work revealed four periods of frequent flooding lasting between 30 and 100 years each: 1560–1590, 1740–1790, 1820–1940, and since 1970. Schmocker-Fackel and Naef report the first three periods of intervening low flood frequency (1500–1560, 1590–1740, and 1790–1810) were found to correspond to periods of low solar activity. However, they note, "after 1810 no relationship between solar activity and flood frequency was found, nor could a relationship be established between reconstructed North Atlantic Oscillation indices or reconstructed Swiss temperatures." In addition, they determined "the current period of increased flood frequencies has not yet exceeded those observed in the past." They also note "a comparison with the flood patterns of other European rivers suggests that flood frequencies are not in phase over Europe."

Schmocker-Fackel and Naef conclude "the current period with more floods in northern Switzerland, which started in the mid 1970s, might continue for some decades," even under conditions of "natural climatic variation."

Stewart *et al*. (2011) note "regional climate models project that future climate warming in Central Europe will bring more intense summer-autumn heavy precipitation and floods as the atmospheric concentration of water vapor increases and cyclones intensify," citing the studies of Arnell and Liu (2001), Christensen and Christensen (2003), and Kundzewicz *et al*. (2005). They derived "a complete record of paleofloods, regional glacier length changes (and associated climate phases) and regional glacier advances and retreats (and associated climate transitions) … from the varved sediments of Lake Silvaplana (ca. 1450 BC–AD 420; Upper Engadine, Switzerland)," while indicating "these records provide insight into the behavior of floods (i.e. frequency) under a wide range of climate conditions."

The five researchers report there was "an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June–July–August temperatures" and the frequency of flooding "was reduced during warm and/or dry climates." Reiterating that "the findings of this study suggest that the frequency of extreme summer–autumn precipitation events (i.e. flood events) and the associated atmospheric pattern in the Eastern Swiss Alps was not enhanced during warmer (or drier) periods," Stewart *et al*. acknowledge "evidence could not be found that summer–autumn floods would increase in the Eastern Swiss Alps in a warmer climate of the 21st century," in contrast to the projections of regional climate models that have suggested otherwise.

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7.5.3.6 Multiple Countries

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to multiple countries across Europe.

Starkel (2002) reviewed what is known about the relationship between extreme weather events and the thermal climate of Europe during the Holocene. This review clearly demonstrated more extreme fluvial activity was typically associated with *cooler* time intervals. In recovering from one such period (the Younger Dryas), for example, temperatures in Germany and Switzerland rose by 3–5°C over several decades; "this fast shift," in Starkel's words, "caused a rapid expansion of forest communities, [a] rise in the upper treeline and higher density of vegetation cover," which led to a "drastic" reduction in sediment delivery from slopes to river channels.

Mudelsee *et al*. (2003) analyzed historical documents from the eleventh century to 1850, plus subsequent water stage and daily runoff records from then until 2002, for two of the largest rivers in central Europe: the Elbe and Oder Rivers. For the prior 80 to 150 years, which the IPCC typically describes as a period of unprecedented global warming, they discovered "a decrease in winter flood occurrence in both rivers, while summer floods show[ed] no trend, consistent with trends in extreme precipitation occurrence."

Mudelsee *et al*. (2004) wrote "extreme river floods have had devastating effects in central Europe in recent years," citing as examples the Elbe flood of August 2002, which caused 36 deaths and inflicted damages totaling more than US $15 billion, and the Oder flood of July 1997, which caused 114 deaths and inflicted approximately US $5 billion in damages. They note concern had been expressed "in the Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change," wherein it was stated "current anthropogenic changes in atmospheric composition will add to this risk."

The four researchers reevaluated the quality of data and methods of reconstruction that had previously produced flood histories of the middle parts of the Elbe and Oder rivers back to AD 1021 and 1269, respectively. For both rivers, they found "no significant trends in summer flood risk in the twentieth century," but "significant downward trends in winter flood risk." The latter phenomenon—described as "a reduced winter flood risk during the instrumental period"—they specifically described as "a response to regional warming." Thus their study provided no support for the IPCC's concern that CO_2-induced warming would add to the risk of river flooding in Europe. If anything, their findings suggest just the opposite.

Based on flood loss information obtained from the Emergency Events Database and Natural Hazards Assessment Network, Barredo (2009) developed a 1970–2006 history of normalized monetary flood losses in Europe—including the member states of the European Union along with Norway, Switzerland, Croatia, and the former Yugoslav Republic of Macedonia—by calculating the value of losses that would have occurred if the floods of the past had taken place under the current socioeconomic conditions of the continent, while further removing inter-country price differences by adjusting the losses for purchasing power parities. This work revealed, in the analyst's words, "no evidence of a clear positive trend in normalized flood losses in Europe," and "changes in population, inflation and per capita real wealth are the main factors contributing to the increase of the original raw losses." After removing the influence of socioeconomic factors, the European Commission researcher states, "there remains no evident signal suggesting any influence of anthropogenic climate change on the trend of flood losses in Europe during the assessed period."

Buntgen *et al*. (2010) point out instrumental station measurements, which systematically cover only the past 100–150 years, "hinder any proper assessment of the statistical likelihood of return period, duration and magnitude of climatic extremes," stating "a palaeoclimatic perspective is therefore indispensable to place modern trends and events in a pre-industrial context (Battipaglia *et al*., 2010), to disentangle effects of human greenhouse gas emission from natural forcing and internal oscillation (Hegerl *et al*., 2011), and to constrain climate model simulations and feedbacks of the global carbon cycle back in time (Frank *et al*., 2010)." Buntgen *et al*. "introduce and analyze 11,873 annually resolved and absolutely dated ring width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period," and which "allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations."

The nine researchers state their data revealed "a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming." This finding, the authors write, "may question the common belief that frequency and severity of such events closely relates to climate mean states."

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7.5.3.7 Other European Countries

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to other countries in Europe not previously discussed in prior subsections of this topic.

7.5.3.7.1 Norway

Nesje *et al*. (2001) analyzed a sediment core from a lake in southern Norway in an attempt to determine the frequency and magnitude of prior floods in that region. The last thousand years of the record revealed "a period of little flood activity around the Medieval period (AD 1000–1400)," followed by a period of extensive flood activity associated with the "post-Medieval climate deterioration characterized by lower air temperature, thicker and more long-lasting snow cover, and more frequent storms associated with the 'Little Ice Age.'" Thus this study suggests the post-Little Ice Age warming Earth has experienced for the last century or two—which could continue for some time to come—should be leading this portion of the planet into a period of less extensive flooding as opposed to the more extensive flooding typically predicted by climate models to occur in response to warming.

7.5.3.7.2 Finland

According to Korhonen and Kuusisto (2010), "annual mean temperatures in Finland increased by about 0.7°C during the 20th century," citing Jylha *et al*. (2004), while noting under such a warming regime, "both droughts and floods are expected to intensify." The two Finnish researchers analyzed long-term trends and variability in the discharge regimes of regulated and unregulated rivers and lake outlets in Finland to 2004, using data supplied by the Finnish Environment Institute.

They found as "winters and springs became milder during the 20th century ... the peak of spring flow has become 1–8 days earlier per decade at over one-third of all studied sites." They further noted "the magnitudes of spring high flow have not changed." Low flows, by contrast, "have increased at about half of the unregulated sites due to an increase in both winter and summer discharges." They conclude, "statistically significant overall changes have not been observed in mean annual discharge." Thus, in contrast to typical global warming projections, at the high end where flooding may occur, there has been no change in the magnitude of flows. At the low end, where droughts may occur, there has been an increase in flow magnitude, which acts to prevent or leads to less frequent and/or less severe episodes of drought.

7.5.3.7.3 Slovakia

Stankoviansky (2003) employed topographical maps and aerial photographs, field geomorphic investigation, and the study of historical documents, including those from local municipal and church sources, to determine the spatial distribution of gully landforms and the temporal history of their creation in the Myjava Hill Land of Slovakia, situated in the western part of the country near its border with the Czech Republic. He found "the central part of the area, settled between the second half of the 16th and the beginning of the 19th centuries, was affected by gully formation in two periods, the first between the end of the 16th century and the 1730s and the second roughly between the 1780s and 1840s." He determined these gullies were formed "during periods of extensive forest clearance and expansion of farmland," but "the triggering mechanism of gullying was extreme rainfalls during the Little Ice Age." He notes "the gullies were formed relatively quickly by repeated incision of ephemeral flows concentrated during extreme rainfall events, which were clustered in periods that correspond with known climatic fluctuations during the Little Ice Age." Subsequently, from the mid-nineteenth century to the present, he reports "there has been a decrease in gully growth because of the afforestation of gullies and especially climatic improvements since the termination of the Little Ice Age."

7.5.3.7.4 Sweden

Lindstrom and Bergstrom (2004) analyzed runoff and flood data from more than 60 discharge stations throughout Sweden, some of which provided information stretching as far back in time as the early 1800s, when Sweden and the world were still experiencing the cold of the Little Ice Age. They discovered the last 20 years of the past century were indeed unusually wet, with a runoff anomaly of +8% compared with the century average. But they also found "the runoff in the 1920s was comparable to that of the two latest decades," and "the few observation series available from the 1800s show that the runoff was even higher than recently." In addition, they determined "flood peaks in old data [were] probably underestimated," which "makes it difficult to conclude that there has really been a significant increase in average flood levels." They also state "no increased frequency of floods with a return period of 10 years or more, could be determined."

Lindstrom and Bergstrom conclude conditions in Sweden "are consistent with results reported from nearby countries: e.g. Forland *et al*. (2000), Bering Ovesen *et al*. (2000), Klavins *et al*. (2002) and Hyvarinen (2003)," and "in general, it has been difficult to show any convincing evidence of an increasing magnitude of floods (e.g. Roald, 1999) in the near region, as is the case in other parts of the world (e.g. Robson *et al*., 1998; Lins and Slack, 1999; Douglas *et al*., 2000; McCabe and Wolock, 2002; Zhang *et al*., 2001)."

7.5.3.7.5 Poland

Cyberski *et al*. (2006) used documentary sources of information (written documents and "flood boards") to develop a reconstruction of winter flooding of the Vistula River in Poland back to AD 988. This work indicated, in their words, that winter floods "have exhibited a decreasing frequency of snowmelt and ice-jam floods in the warming climate over much of the Vistula basin." In addition, they report the work of Pfister (2005) indicates most of Central Europe also has become less drought-prone in winter during the twentieth century. It would appear twentieth century global warming has been accompanied by reductions in floods and droughts in much of Central Europe, just the opposite of model-based projections.

7.5.3.7.6 Italy

Diodato *et al*. (2008) undertook a detailed analysis of "the Calore River Basin (South Italy) erosive rainfall using data from 425-year-long series of both observations (1922–2004) and proxy-based reconstructions (1580–1921)." This work revealed pronounced interdecadal variations, "with multi-decadal erosivity reflecting the mixed population of thermo-convective and cyclonic rainstorms with large anomalies," and they note "the so-called Little Ice Age (16th to mid-19th centuries) was identified as the stormiest period, with mixed rainstorm types and high frequency of floods and erosive rainfall."

The three researchers conclude, "in recent years, climate change (generally assumed as synonymous with global warming) has become a global concern and is widely reported in the media." With respect to the concern that both droughts and floods will become both more frequent and more severe as the planet warms, they say their study indicates "climate in the Calore River Basin has been largely characterized by naturally occurring weather anomalies in past centuries (long before industrial CO_2 emissions), not only in recent years," and there has been a "relevant smoothing" of such events during the modern era.

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7.5.4 North America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to North America.

Lins and Slack (1999) analyzed secular streamflow trends in 395 parts of the United States derived from more than 1,500 individual stream gauges, some of which had continuous data stretching back to 1914. In the mean, they found "the conterminous U.S. is getting wetter, but less extreme." That is to say, as the near-surface air temperature of the planet gradually rose throughout the twentieth century, the United States became wetter in the mean but less variable at the extremes, which is where floods and droughts occur, leading to what could be considered the best of both worlds: more water with fewer floods.

Molnar and Ramirez (2001) conducted a detailed analysis of precipitation and streamflow trends for the period 1948–1997 in the semiarid Rio Puerco Basin of New Mexico. At the annual timescale, they reported finding "a statistically significant increasing trend in precipitation," driven primarily by an increase in the number of rainy days in the moderate rainfall intensity range with essentially no change at the high-intensity end of the spectrum. In the case of streamflow, there was no trend at the annual timescale, but monthly totals increased in low-flow months and decreased in high-flow months, once again reducing the likelihood of both floods and droughts.

Increased precipitation in a semiarid region would seem to be a good thing. Having most of the increase arrive in the moderate rainfall intensity range also would appear to be a good thing. Increasing streamflow in normally low-flow months sounds good too, as does decreasing streamflow in high-flow months. The changes in precipitation and streamflow observed by Molnar and Ramirez would appear to be highly desirable, leading to more water availability but a lowered probability of both floods and droughts.

Knox (2001) identified an analogous phenomenon in the more mesic Upper Mississippi River Valley. Since the 1940s and early 1950s, the magnitudes of the largest daily flows in this much wetter region have been decreasing while the magnitude of the average daily baseflow has been increasing, once again manifesting simultaneous trends towards both lessened flood and drought conditions.

Garbrecht and Rossel (2002) studied the nature of precipitation throughout the U.S. Great Plains over the period 1895–1999. For the central and southern Great Plains, the last two decades of this period were found to be the longest and wettest of the 105 years of record, due primarily to a reduction in the number of dry years and an increase in the number of wet years. Once again, however, the number of very wet years, which would be expected to produce flooding, "did not increase as much and even showed a decrease for many regions."

The northern and northwestern Great Plains experienced a precipitation increase near the end of Garbrecht and Rossel's 105-year record, but the increase was confined primarily to the final decade of the twentieth century. As they report, "fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions."

The last decade of the past century did produce significant floods, such as the 1997 flooding of the Red River of the North, which devastated Grand Forks, North Dakota as well as parts of Canada. As Haque (2000) reports, this flood was the largest in the Red River over the past century, but it was not the largest in historic times. In 1852, for example, there was a slightly larger Red River flood, and in 1826 there was a flood nearly 40% greater than that of 1997. The temperature of the globe was much colder at the times of these earlier catastrophic floods than it was in 1997, suggesting one cannot attribute the strength of the 1997 flood to the degree of warmth experienced that year or the preceding decade.

Olsen *et al*. (1999) report some upward trends in flood-flows have been found in certain places along the Mississippi and Missouri Rivers; there will always be exceptions to the general rule. At the same time, they note many of the observed upward trends were highly dependent upon the length of the data record and when the trends began and ended. Hence, they say these trends "were not necessarily there in the past and they may not be there tomorrow."

Pinter *et al*. (2008) also tested for long-term changes in flood magnitudes and frequencies in the Mississippi River system. They "constructed a hydrologic database consisting of data from 26 rated stations (with both stage and discharge measurements) and 40 stage-only stations." Then, to help "quantify changes in flood levels at each station in response to construction of wing dikes, bendway weirs, meander cutoffs, navigational dams, bridges, and other modifications," the researchers compiled a geospatial database consisting of "the locations, emplacement dates, and physical characteristics of over 15,000 structural features constructed along the study rivers over the past 100–150 years." Pinter *et al*. say "significant climate- and/or land use-driven increases in flow were detected," but "the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures, followed by progressive levee construction."

Pinter *et al*. write "the navigable rivers of the Mississippi system have been intensively engineered, and some of these modifications are associated with large decreases in the rivers' capacity to convey flood flows." It would appear man may indeed have been responsible for most of the enhanced flooding of the rivers of the Mississippi system over the past century or so, but not in the way suggested by the IPCC. The question that needs addressing by the region's inhabitants, therefore, has nothing to do with CO_2, but everything to do with how to "balance the local benefits of river engineering against the potential for large-scale flood magnification."

Similar findings have been reported for the Upper Midwest (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, and Illinois) by Villarini *et al*. (2011), who "analyzed the annual maximum instantaneous flood peak distributions for 196 U.S. Geological Survey streamflow stations with a record of at least 75 years over the Midwest U.S." According to the four U.S. researchers, the majority of streamflow changes they observed were "associated with change-points (both in mean and variance) rather than monotonic trends," and they indicated "these non-stationarities are often associated with anthropogenic effects." But rather than associate the increases with anthropogenic CO_2 emissions, they cite such things as "changes in land use/land cover, changes in agricultural practice, and construction of dams and reservoirs" as the primary cause(s). "In agreement with previous studies (Olsen *et al*., 1999; Villarini *et al*., 2009)," they conclude "there is little indication that anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S." And as they make doubly clear in the abstract of their paper, "trend analyses do not suggest an increase in the flood peak distribution due to anthropogenic climate change."

Villarini and Smith (2010) "examined the distribution of flood peaks for the eastern United States using annual maximum flood peak records from 572 U.S. Geological Survey stream gaging stations with at least 75 years of observations." This work revealed, "in general, the largest flood magnitudes are concentrated in the mountainous central Appalachians and the smallest flood peaks are concentrated along the low-gradient Coastal Plain and in the northeastern United States." They also found "landfalling tropical cyclones play an important role in the mixture of flood generating mechanisms, with the frequency of tropical cyclone floods exhibiting large spatial heterogeneity over the region." They also note "warm season thunderstorm systems during the peak of the warm season and winter-spring extratropical systems contribute in complex fashion to the spatial mixture of flood frequency over the eastern United States."

Of even greater interest to the climate change debate, they found "only a small fraction of stations exhibited significant linear trends," and "for those stations with trends, there was a split between increasing and decreasing trends." They also note "no spatial structure was found for stations exhibiting trends." Thus, they conclude, "there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States."

Much the same was reported for Canada by Cunderlik and Ouarda (2009), who evaluated trends in the timing and magnitude of seasonal maximum flood events based on data obtained from 162 stations of the Reference Hydrometric Basin Network established by Environment Canada over the 30-year period 1974–2003. The Canadian researchers report finding "only 10% of the analyzed stations show significant trends in the timing of snowmelt floods during the last three decades (1974–2003)," and they say these results imply "the occurrence of snowmelt floods is shifting towards the earlier times of the year," as would be expected in a warming world. They note most of the identified trends "are only weakly or medium significant results" and "no significant trends were found in the timing of rainfall-dominated flood events."

With respect to flood magnitudes, the two scientists state the trends they observed "are much more pronounced than the trends in the timing of the floods," but most of these trends "had negative signs, suggesting that the magnitude of the annual maximum floods has been decreasing over the last three decades." In addition, they found "the level of significance was also higher in these trends compared to the level of significance of the trends in the timing of annual maximum floods."

A number of studies have examined floods over much longer intervals of time. Wolfe *et al*. (2005), for example, conducted a multiproxy hydroecological analysis of Spruce Island Lake (58°51'N, 111°29'W), a shallow, isolated, upland lake in a bedrock basin located in the northern Peace sector of the Peace-Athabasca Delta in northern Alberta, Canada, in an attempt to assess the impacts of both natural variability and anthropogenic change on the hydroecology of the region over the past 300 years. Specifically, their research was designed to answer three questions: (1) Have hydroecological conditions in Spruce Island Lake since 1968 (the year in which river flow became regulated from hydroelectric power generation at the headwaters of the Peace River) varied beyond the range of natural variation of the past 300 years? (2) Is there evidence that flow regulation of the Peace River has caused significant changes in hydroecological conditions in Spruce Island Lake? (3) How is hydroecological variability at Spruce Island Lake related to natural climatic variability and Peace River flood history?

Wolfe *et al*.'s research revealed hydroecological conditions varied substantially over the past 300 years, especially in terms of multidecadal dry and wet periods. For question #1, the authors found hydroecological conditions after 1968 have remained well within the broad range of natural variability observed over the past 300 years, with both "markedly wetter and drier conditions compared to recent decades" having occurred prior to the time of Peace River flow regulation. With respect to question #2, they note the current drying trend is not the product of Peace River flow regulation, but rather the product of an extended drying period initiated in the early to mid-1900s. Lastly, with respect to question #3, Wolfe *et al*. found the multi-proxy hydro-ecological variables they analyzed were well correlated with other reconstructed records of natural climate variability, indicating a likely climatic influence on Spruce Island Lake hydroecological conditions over the period of record.

Thus there is nothing unusual about recent trends in the hydroecology of the Spruce Island Lake region. Wet and dry conditions of today fall well within the range of natural variability and show no fingerprint of anthropogenic global warming. What is more, they even bear no fingerprint of anthropogenic flow control on the Peace River since 1968, demonstrating, in the words of the authors, that "profound changes in hydro-ecological conditions are clearly a natural feature of this ecosystem, independent of human influence or intervention."

Shapley *et al*. (2005) developed a 1,000-year hydroclimate reconstruction from local bur oak (*Quercus macrocarpa*) tree-ring records and lake sediment cores from the Waubay Lake complex located in eastern South Dakota. During the 1990s, broad areas of the U.S. Northern Great Plains experienced notable lake highstands. Waubay Lake, for example, rose by 5.7 meters and more than doubled in area from 1993 to 1999, severely flooding roads, farms, and towns and prompting the Federal Emergency Management Agency to declare the region a disaster area on 1 June 1998. Shapley *et al*. set out to determine the historical context of that 1990s lake-level rise.

The researchers found "prior to AD 1800, both lake highstands and droughts tended towards greater persistence than during the past two centuries," such that "neither generally low lake levels occurring since European settlement (but before the recent flooding) nor the post-1930s pattern of steadily increasing water availability and favorableness for tree growth are typical of the long-term record." In this particular part of the world, longer-lasting floods and droughts of equal or greater magnitude than those of modern times occurred repeatedly prior to 1800.

Fye *et al*. (2003) developed multicentury reconstructions of summer (June–August) Palmer Drought Severity Index over the continental United States from annual proxies of moisture status provided by 426 climatically sensitive tree-ring chronologies. They found the greatest twentieth century wetness anomaly across the United States was the 13-year pluvial that occurred in the early part of the century, when it was considerably colder than it is now. Fye *et al*.'s analysis also revealed the existence of a 16-year pluvial from 1825 to 1840 and a prolonged 21-year wet period from 1602 to 1622, both of which occurred during the Little Ice Age.

St. George and Nielsen (2002) used "a ringwidth chronology developed from living, historical and subfossil bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin to reconstruct annual precipitation in southern Manitoba since A.D. 1409." They found, "prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement."

Ni *et al*. (2002) used tree-ring chronologies to develop a 1,000-year history of cool-season (November–April) precipitation for each climate division in Arizona and New Mexico, USA. They found several wet periods comparable to the wet conditions seen in the early 1900s and post-1976 occurred in 1108–1120, 1195–1204, 1330–1345 (which they denote "the most persistent and extreme wet interval"), the 1610s, and the early 1800s. All of these wet periods are embedded in the long cold expanse of the Little Ice Age.

Ely (1997) wrote "paleoflood records from nineteen rivers in Arizona and southern Utah, including over 150 radiocarbon dates and evidence of over 250 flood deposits, were combined to identify regional variations in the frequency of extreme floods," and this information "was then compared with paleoclimatic data to determine how the temporal and spatial patterns in the occurrence of floods reflect the prevailing climate." The results of this comparison indicated "long-term variations in the frequency of extreme floods over the Holocene are related to changes in the climate and prevailing large-scale atmospheric circulation patterns that affect the conditions conducive to extreme flood-generating storms in each region." These changes, in Ely's view, "are very plausibly related to global-scale changes in the climate system."

With respect to the Colorado River watershed, for example, which integrates a large portion of the interior western United States, she writes "the largest floods tend to be from spring snowmelt after winters of heavy snow accumulation in the mountains of Utah, western Colorado, and northern New Mexico," such as occurred with the "cluster of floods from 5 to 3.6 ka," which occurred in conjunction with "glacial advances in mountain ranges throughout the western United States" during the "cool, wet period immediately following the warm mid-Holocene."

The frequency of extreme floods also increased during the early and middle portions of the first millennium AD, many of which coincided "with glacial advances and cool, moist conditions both in the western U.S. and globally." Then came a "sharp drop in the frequency of large floods in the southwest from AD 1100–1300," which corresponded, in her words, "to the widespread Medieval Warm Period, which was first noted in European historical records." With the advent of the Little Ice Age, there was another "substantial jump in the number of floods in the southwestern U.S.," which was "associated with a switch to glacial advances, high lake levels, and cooler, wetter conditions."

Distilling her findings to a single succinct statement, and speaking specifically of the south-western United States, Ely writes, "global warm periods, such as the Medieval Warm Period, are times of dramatic decreases in the number of high-magnitude floods in this region."

Schimmelmann *et al*. (2003) analyzed gray clay-rich flood deposits in the predominantly olive varved sediments of the Santa Barbara Basin off the coast of California, USA, which they accurately dated by varve-counting. They found six prominent flood events at approximately AD 212, 440, 603, 1029, 1418, and 1605, "suggesting," in their words, "a quasi-periodicity of ~200 years," with "skipped" flooding just after AD 800, 1200, and 1800. They further note "the floods of ~AD 1029 and 1605 seem to have been associated with brief cold spells"; "the flood of ~AD 440 dates to the onset of the most unstable marine climatic interval of the Holocene (Kennett and Kennett, 2000)"; and "the flood of ~AD 1418 occurred at a time when the global atmospheric circulation pattern underwent fundamental reorganization at the beginning of the 'Little Ice Age' (Kreutz *et al*., 1997; Meeker and Mayewski, 2002)." They hypothesize "solar-modulated climatic background conditions are opening a ~40-year window of opportunity for flooding every ~200 years," and "during each window, the danger of flooding is exacerbated by additional climatic and environmental cofactors." They also note "extrapolation of the ~200-year spacing of floods into the future raises the uncomfortable possibility for historically unprecedented flooding in southern California during the first half of this century." If such flooding occurs in the near future, there will be no need to suppose it came as a consequence of what the IPCC calls the unprecedented warming of the past century.

Campbell (2002) analyzed the grain sizes of sediment cores obtained from Pine Lake, Alberta, Canada, to provide a non-vegetation-based high-resolution record of streamflow variability for this part of North America over the past 4,000 years. This work revealed the highest rates of stream discharge during this period occurred during the Little Ice Age, approximately 300–350 years ago, at which time grain sizes were about 2.5 standard deviations above the 4,000-year mean. In contrast, the lowest rates of streamflow were observed around AD 1100, during the Medieval Warm Period, when median grain sizes were nearly 2.0 standard deviations below the 4,000-year mean.

Carson *et al*. (2007) developed a Holocene history of flood magnitudes from reconstructed cross-sectional areas of abandoned channels and relationships relating channel cross-sections to flood magnitudes derived from modern stream gauge and channel records for the northern Uinta Mountains of northeastern Utah. Carson *et al*. report over the past 5,000 years the record of bankfull discharge "corresponds well with independent paleoclimate data for the Uinta Mountains," and "during this period, the magnitude of the modal flood is smaller than modern during warm dry intervals and greater than modern during cool wet intervals," noting most particularly "the decrease in flood magnitudes following 1000 cal yr B.P. corresponds to numerous local and regional records of warming during the Medieval Climatic Anomaly." The three largest negative departures from modern bankfull flood magnitudes (indicating greater than modern warmth) range approximately 15–22%, as best as can be determined from visual inspection of their plotted data, and they occur between about 750 and 600 cal yr B.P., as determined from radiocarbon dating of basal channel-fill sediments.

Carson *et al*.'s findings demonstrate the degree of natural variability in northeastern Utah flood magnitudes throughout the Holocene has been much larger (in both positive and negative directions) than what has been observed in modern times. Moreover, their work demonstrates the portion of the Medieval Warm Period between about AD 1250 and 1400 was likely significantly warmer than it is at present. Something other than high concentrations of atmospheric CO_2 was responsible for the region's warmth at that time, and thus one need not invoke today's much higher CO_2 concentrations as the reason for our actually lower current temperatures.

Brown *et al*. (1999) analyzed properties of cored sequences of hemipelagic muds deposited in the northern Gulf of Mexico for evidence of variations in Mississippi River outflow over the past 5,300 years. They found evidence of seven large megafloods, which they describe as "almost certainly larger than historical floods in the Mississippi watershed." They say these fluvial events were likely "episodes of multidecadal duration," five of which occurred during cold periods similar to the Little Ice Age.

Noren *et al*. (2002) employed several techniques to identify and date terrigenous in-wash layers found in sediment cores extracted from 13 small lakes distributed across a 20,000-km^2 region in Vermont and eastern New York that depict the frequency of storm-related floods. Their results indicate "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." Specifically, they found four major peaks in the data during this period, with the most recent upswing in storm-related floods beginning "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." In addition, they note several "independent records of storminess and flooding from around the North Atlantic show maxima that correspond to those that characterize our lake records [Brown *et al*., 1999; Knox, 1999; Lamb, 1979; Liu and Fearn, 2000; Zong and Tooley, 1999]."

Hirsch and Ryberg (2012) point out "one of the anticipated hydrological impacts of increases in greenhouse gas concentrations in the atmosphere is an increase in the magnitude of floods," citing Trenberth (1999), the IPCC (2007), and Gutowski *et al*. (2008). Working with the global mean carbon dioxide concentration (GMCO2) and a streamflow dataset consisting of long-term (85- to 127-year) annual flood series from 200 stream gauges deployed by the U.S. Geological Survey in basins with little or no reservoir storage or urban development (less than 150 persons per square kilometer in AD 2000) throughout the conterminous United States, which they divided into four large regions, Hirsch and Ryberg employed a stationary bootstrapping technique to determine whether the patterns of the statistical associations between the two parameters were significantly different from what would be expected under the null hypothesis that flood magnitudes are independent of GMCO2.

The two researchers report "in none of the four regions defined in this study is there strong statistical evidence for flood magnitudes increasing with increasing GMCO2." One region, the southwest, showed a statistically significant negative relationship between GMCO2 and flood magnitudes. Hirsch and Ryberg conclude "it may be that the greenhouse forcing is not yet sufficiently large to produce changes in flood behavior that rise above the 'noise' in the flood-producing processes."It could also mean the "anticipated hydrological impacts" envisioned by the IPCC and others are simply incorrect.

Taken together, the research described in this subsection suggest, if anything, that North American flooding tends to become less frequent and less severe when the planet warms, although there have been exceptions to this general rule. Although there could be exceptions to this rule in the future, it is more likely than not that any further warming of the globe would tend to further reduce both the frequency and severity of flooding in North America—just the opposite of what climate models suggest would occur.

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7.5.5 South America

As indicated in the introduction of Section 7.5, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent, more severe, and longer-lasting floods. This subsection highlights such research as it pertains to South America.

River flow records in southern South America, according to Mundo *et al*. (2012), "extend for only a few decades, hampering the detection of long-term, decadal to centennial-scale cycles and trends," which are needed in order to ascertain the degree of validity of model-based claims for that part of the world.

To extend the streamflow history of Argentina's Neuquen River—which Mundo *et al*. say is of "great importance for local and national socio-economic activities such as hydroelectric power generation, agriculture and tourism"—the authors employed 43 new and updated tree-ring chronologies from a network of *Araucaria araucana* and *Austrocedrus chilensis* trees in reconstructing the October–June mean streamflow of the river for each year of the 654-year period AD 1346–2000, using a nested principal component regression approach.

In terms of the frequency, intensity, and duration of droughts and pluvial events, the eight researchers determined "the 20th century contains some of the driest and wettest annual to decadal-scale events in the last 654 years." They also report "longer and more severe events were recorded in previous centuries."

Rein *et al*. (2004) derived a high-resolution flood record of the entire Holocene from an analysis of the sediments in a 20-meter core retrieved from a sheltered basin situated on the edge of the Peruvian shelf about 80 km west of Lima, Peru. The authors reported finding a major Holocene anomaly in the flux of lithic components from the continent onto the Peruvian shelf during the late Medieval period. "Lithic concentrations were very low for about 450 years during the Medieval climatic anomaly from A.D. 800 to 1250," they report, indicating a sustained period absent of large floods. They state "all known terrestrial deposits of El Niño mega-floods (Magillian and Goldstein, 2001; Wells, 1990) precede or follow the medieval anomaly in our marine records and none of the El Niño mega-floods known from the continent date within the marine anomaly." In addition, they note "this precipitation anomaly also occurred in other high-resolution records throughout the ENSO domain," citing 11 references.

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7.6 Precipitation

The IPCC and others claim global warming will cause greater variability in precipitation, frequently manifested in climate models as more frequent and heavier rainfall events. The IPCC has stated "in the near term, it is likely that the frequency and intensity of heavy precipitation events will increase at the global scale and at high latitudes" (p. 12 of the Summary for Policymakers, Second Order Draft of AR5, dated October 5, 2012). The IPCC expects changes in average precipitation as well; some regions will increase, others will decrease, but on the whole, global precipitation is expected to increase.

General trends in precipitation are examined in Chapter 6 of this volume, where observational data indicate there is nothing unusual or unprecedented about recent precipitation events and trends in most regions, suggesting rising atmospheric CO_2 is having no measurable effect on precipitation totals. This section focuses on the variability or extremeness of precipitation, seeking to determine whether there is compelling evidence from historical observations that recent changes, if they are occurring, are the product of Earth's rising atmospheric CO_2 concentration.

As revealed in the subsections below, numerous studies suggest there is, in fact, no CO_2 influence on the variability or extremeness of precipitation. Moisture extremes much greater than those observed in the modern era have occurred throughout the historic past. Recent trends and events are neither unusual nor manmade; they are simply a normal part of Earth's natural climatic variability.

7.6.1 Africa

Nicholson and Yin (2001) describe climatic and hydrologic conditions in equatorial East Africa from the late 1700s to close to the present, based on histories of the levels of 10 major African lakes. They also use a water balance model to infer changes in rainfall associated with the different conditions, concentrating most heavily on Lake Victoria. This work reveals "two starkly contrasting climatic episodes." The first, which began sometime prior to 1800 and was characteristic of Little Ice Age conditions, was one of "drought and desiccation throughout Africa." This arid episode, which was most extreme during the 1820s and 1830s, was accompanied by extremely low lake levels. As the two researchers describe it, "Lake Naivash was reduced to a puddle ... Lake Chad was desiccated ... Lake Malawi was so low that local inhabitants traversed dry land where a deep lake now resides ... Lake Rukwa [was] completely desiccated ... Lake Chilwa, at its southern end, was very low and nearby Lake Chiuta almost dried up." Throughout this period, they report, "intense droughts were ubiquitous." Some were "long and severe enough to force the migration of peoples and create warfare among various tribes."

As the Little Ice Age's grip on the world began to loosen in the mid to late 1800s, things began to improve for most of the continent. Nicholson and Yin report "semi-arid regions of Mauritania and Mali experienced agricultural prosperity and abundant harvests, ... the Niger and Senegal Rivers were continually high; and wheat was grown in and exported from the Niger Bend region." Across the length of the northern Sahel, maps and geographical reports described the presence of "forests." As the nineteenth century came to an end and the twentieth century began, there was a slight lowering of lake levels, but nothing like what had occurred a century earlier (i.e., the precipitation variability was much reduced). In the latter half of the twentieth century, the levels of some of the lakes rivaled the high-stands characteristic of the years of transition to the Current Warm Period.

Nicholson (2001) reports the most significant climatic change in the more recent past has been "a long-term reduction in rainfall in the semi-arid regions of West Africa," which has been "on the order of 20 to 40% in parts of the Sahel." There have been, she states, "three decades of protracted aridity," and "nearly all of Africa has been affected ... particularly since the 1980s." She goes on to note "the rainfall conditions over Africa during the last 2 to 3 decades are not unprecedented" and "a similar dry episode prevailed during most of the first half of the 19th century."

Nicholson says "the 3 decades of dry conditions evidenced in the Sahel are not in themselves evidence of irreversible global change," because a longer historical perspective indicates an even longer period of similar dry conditions occurred between 1800 and 1850. This dry period occurred when Earth was still in the clutches of the Little Ice Age, a period of cold that is without precedent in at least the past 6,500 years, even in Africa (Lee-Thorp *et al*., 2001). There is therefore no reason to consider the most recent two- to three-decade Sahelian drought as unusual or the result of higher temperatures of that period.

Nguetsop *et al*. (2004) developed a high-resolution proxy record of West African precipitation based on analyses of diatoms recovered from a sediment core retrieved from Lake Ossa, West Cameroon, which they describe as "the first paleohydrological record for the last 5500 years in the equatorial near-coastal area, east of the Guinean Gulf." They report this record provides evidence for alternating periods of increasing and decreasing precipitation "at a millennial time scale for the last 5500 years," and they interpret this oscillatory behavior as being "a result of south/northward shifts of the Intertropical Convergence Zone," specifically noting "a southward shift of the ITCZ, combined with strengthened northern trade winds, was marked by low and high precipitation at the northern subtropics and the subequatorial zone, respectively," and "these events occurred in coincidence with cold spells in the northern Atlantic."

Therrell *et al*. (2006) developed "the first tree-ring reconstruction of rainfall in tropical Africa using a 200-year regional chronology based on samples of *Pterocarpus angolensis* [a deciduous tropical hardwood known locally as Mukwa] from Zimbabwe." This record revealed "a decadal-scale drought reconstructed from 1882 to 1896 matches the most severe sustained drought during the instrumental period (1989–1995)," and "an even more severe drought is indicated from 1859 to 1868 in both the tree-ring and documentary data." They report the year 1860, which exhibited the lowest reconstructed rainfall value during this period, was described in a contemporary account from Botswana (where part of their tree-ring chronology originated) as "a season of 'severe and universal drought' with 'food of every description' being 'exceedingly scarce' and the losses of cattle being 'very severe' (Nash and Endfield, 2002)." At the other end of the moisture spectrum, they report "a 6-year wet period at the turn of the nineteenth century (1897–1902) exceeds any wet episode during the instrumental era."

For a large part of central southern Africa, as well as other parts of the continent described above, it is clear twentieth century global warming has not resulted in an intensification of extreme dry and wet periods. If anything, just the opposite appears to have occurred.

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7.6.2 Asia

Pederson *et al*. (2001) developed tree-ring chronologies for northeastern Mongolia to reconstruct annual precipitation and streamflow histories for the period 1651–1995. Working with both standard deviations and 5-year intervals of extreme wet and dry periods, they found "variations over the recent period of instrumental data are not unusual relative to the prior record." They note, however, their reconstructions "appear to show more frequent extended wet periods in more recent decades," but this observation "does not demonstrate unequivocal evidence of an increase in precipitation as suggested by some climate models." Spectral analysis of the data also revealed significant periodicities around 12 and 20–24 years, which they suggested may constitute "possible evidence for solar influences in these reconstructions for northeastern Mongolia."

Davi *et al*. (2006) used absolutely dated tree-ring-width chronologies obtained from five sampling sites in west-central Mongolia to derive individual precipitation histories, the longest of which stretches from 1340 to 2002, additionally developing a reconstruction of streamflow that extends from 1637 to 1997. They discovered there was "much wider variation in the long-term tree-ring record than in the limited record of measured precipitation," which for the region they studied covers the period from 1937 to 2003. In addition, they say their streamflow history indicates "the wettest 5-year period was 1764–68 and the driest period was 1854–58," and "the most extended wet period [was] 1794–1802 and ... extended dry period [was] 1778–83."

Liu *et al*. (2012) state "climate change is consistently associated with changes in a number of components of the hydrological cycle," including "precipitation patterns and intensity, and extreme weather events." Therefore, and in order to "provide advice for water resource management under climate change," they conducted a study of the subject in the Guangdong Province of Southern China, which occupies a land area of approximately 178,000 km^2 and has a population of just over 96 million people (as of 2009). The authors analyzed "trends of annual, seasonal and monthly precipitation in southern China (Guangdong Province) for the period 1956–2000 ... based on the data from 186 high-quality gauging stations," and they employed "statistical tests, including the Mann-Kendall rank test and wavelet analysis," to determine whether the precipitation series exhibited any regular trends or periodicities.

The four researchers report "annual precipitation has a slightly decreasing trend in central Guangdong and slight increasing trends in the eastern and western areas of the province," but "all the annual trends are not statistically significant at the 95% confidence level." They discovered "average precipitation increases in the dry season in central Guangdong, but decreases in the wet season," such that "precipitation becomes more evenly distributed within the year." They state "the results of wavelet analysis show prominent precipitation with periods ranging from 10 to 12 years in every sub-region in Guangdong Province." Comparing precipitation with the 11-year sunspot cycle, they find "the annual precipitation in every sub-region in Guangdong province correlates with Sunspot Number with a 3-year lag." Thus, rather than becoming more extreme in the face of 1956–2000 global warming, precipitation in China's Guangdong Province appears to have become both less extreme and less variable. The precipitation patterns that emerge upon proper analysis suggest the primary player in their determination is the Sun.

Ji *et al*. (2005) used reflectance spectroscopy on a sediment core taken from a lake in the northeastern part of the Qinghai-Tibetan Plateau to obtain a continuous high-resolution proxy record of the Asian monsoon over the past 18,000 years. They found monsoonal moisture since the late glacial period had been subject to "continual and cyclic variations," among which was a "very abrupt onset and termination" of a 2,000-year dry spell that started about 4,200 years ago (yr BP) and ended around 2300 yr BP. Other variations included the well-known centennial-scale cold and dry spells of the Dark Ages Cold Period (DACP) and Little Ice Age (LIA), which lasted from 2100 yr BP to 1800 yr BP and 780 yr BP to 400 yr BP, respectively, while sandwiched between them was the warmer and wetter Medieval Warm Period, and preceding the DACP was the Roman Warm Period.

Time series analyses of the sediment record also revealed several statistically significant periodicities (123, 163, 200, and 293 years, all above the 95% level), with the 200-year cycle matching the de Vries or Suess solar cycle, implying changes in solar activity are important triggers for some of the recurring precipitation changes in that part of Asia. Ji *et al.*'s study shows large and abrupt fluctuations in the Asian monsoon have occurred numerous times and with great regularity throughout the Holocene, and the Sun played an important role in orchestrating those fluctuations.

Shao *et al*. (2005) used seven Qilian juniper ring-width chronologies from the northeastern part of the Qaidam Basin in the Tibetan Plateau to reconstruct a thousand-year history of annual precipitation. They discovered annual precipitation had fluctuated at various intervals and to various degrees throughout the past millennium. Wetter periods occurred between 1520 and 1633, as well as between 1933 and 2001, although precipitation has declined somewhat since the 1990s. Drier periods occurred between 1429 and 1519 and between 1634 and 1741. With respect to variability, the scientists report the magnitude of variation in annual precipitation was about 15 mm before 1430, increased to 30 mm between 1430 and 1850, and declined thereafter to the present. These findings together suggest the planet's current warmth is not unprecedented relative to that of the early part of the past millennium, or unprecedented warming need not lead to unprecedented precipitation or unprecedented precipitation variability, or both. This study does not provide support for the contention that global warming leads to greater and more frequent precipitation extremes.

Zhang *et al*. (2007) developed flood and drought histories of the past thousand years in China's Yangtze Delta "from local chronicles, old and very comprehensive encyclopedia, historic agricultural registers, and official weather reports," upon which "continuous wavelet transform was applied to detect the periodicity and variability of the flood/drought series." In comparing their findings with two one-thousand-year temperature histories from the region, the authors report "colder mean temperature in the Tibetan Plateau usually resulted in higher probability of flood events in the Yangtze Delta region." In addition, during AD 1400–1700 (the coldest portion of their record, corresponding to much of the Little Ice Age), the proxy indicators showed "annual temperature experienced larger variability (larger standard deviation), and this time interval exactly corresponds to the time when the higher and significant wavelet variance occurred" in the flood/drought series.

In contrast, Zhang *et al*. report during AD 1000–1400 (the warmest portion of their record, corresponding to much of the Medieval Warm Period), relatively stable "climatic changes reconstructed from proxy indicators in Tibet correspond to lower wavelet variance of flood/ drought series in the Yangtze Delta region." These findings once again illustrate warmer climates tend to be less variable than colder ones.

Touchan *et al*. (2005) developed summer (May-August) precipitation reconstructions for several parts of the eastern Mediterranean region (Turkey, Syria, Lebanon, Cyprus, and Greece) that extend back in time from 115 to 600 years. Over the latter period of time, they found May–August precipitation varied on multiannual and decadal timescales, but on the whole there were no long-term trends. The longest dry period occurred in the late sixteenth century (1591–1595), and there were two extreme wet periods: 1601–1605 and 1751–1755. In addition, both extremely strong and weak precipitation events were found to be more variable over the intervals 1520–1590, 1650–1670, and 1850–1930. This study thus also demonstrates there was nothing unusual or unprecedented about late-twentieth century precipitation events in the eastern Mediterranean part of Asia that would suggest a CO_2 influence. If anything, as this region transited from the record cold of the Little Ice Age to the peak warmth of the Current Warm Period, May–August precipitation became less variable in the face of rising temperatures.

Kripalani and Kulkarni (2001) studied seasonal summer monsoon (June–September) rainfall data from 120 east Asia stations for the period 1881–1998. A series of statistical tests they applied to these data revealed the presence of short-term variability in rainfall amounts on decadal and longer time scales, the longer "epochs" of which were found to last for about three decades over China and India and for approximately five decades over Japan. No long-term trends were detected. With respect to the decadal variability found in the record, the two researchers say it "appears to be just a part of natural climate variations."

Kishtawal *et al*. (2010) studied the Indian subcontinent (8.2°N to 35.35°N, 68.5°E to 97°E) to assess the impacts of urbanization on the region's rainfall characteristics during the Indian summer monsoon by analyzing *in situ* and satellite-based precipitation and population datasets. The five researchers found "a significantly increasing trend in the frequency of heavy rainfall climatology over urban regions of India during the monsoon season," adding "urban regions experience less occurrences of light rainfall and significantly higher occurrences of intense precipitation compared to non-urban regions."

What is the significance of these findings? In their book *Dire Predictions: Understanding Global Warming*, Mann and Kump (2008) note most climate model simulations of global warming indicate "increases are to be expected in the frequency of very intense rainfall events." Throughout most of the world, however, and as seen in the studies reviewed in this section, that expectation has not been fulfilled. Where increasing frequency of intense rainfall events has been observed in some studies, the findings of Kishtawal *et al*. and the papers they cite suggest urbanization may have been the cause. Moreover, the work of Hossain *et al*. (2009) suggests the proliferation of large dams also may be causing such events to occur. The work reviewed here suggests the only effect CO_2-induced global warming may be having on precipitation variability in Asia is to make it less rather than more variable.

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7.6.3 Europe

Alexandrov *et al*. (2004) analyzed various characteristics of climate in Bulgaria during the twentieth century by applying Meteo-France homogenization procedures to many raw datasets of the country, which procedures included, in their words, "control of monthly data of precipitation and average air temperature from selected weather stations in Bulgaria; detection of breaks and outliers within the collected and controlled time series; correction of the climate long-term series according to the defined breaks and outliers in order to obtain homogenized climate series." They found "no significant warming trend during the last century in Bulgaria in spite of the slight increase of average air temperature during the last two decades." They also note "a decreasing trend in annual and especially summer precipitation from the end of the 1970s was found," and "variations of annual precipitation in Bulgaria showed an overall decrease." Thus, as Bulgaria experienced a slight increase in average air temperature over the past two decades, the variability of annual precipitation decreased.

Ntegeka and Willems (2008) write "long-term temporal analysis of trends and cycles is crucial in understanding the natural variability within the climate system." They performed "an empirical statistical analysis of trends in rainfall extremes ... based on the long-term high-frequency homogeneous rainfall series at the climatological station of the Royal Meteorological Institute of Belgium at Uccle." This series was recorded by "the same measuring instrument at the same location since 1898 and processed with identical quality since that time," and it was done at a measuring frequency of ten minutes, yielding more than 107 years of continuous data.

The Belgian researchers report "significant deviations in rainfall quantiles were found, which persisted for periods of 10 to 15 years," such that "in the winter and summer seasons, high extremes were clustered in the 1910s–1920s, the 1960s and recently in the 1990s." "This temporal clustering," the authors conclude, "highlights the difficulty of attributing 'change' in climate series to anthropogenically induced global warming," and they state "no strong conclusions can be drawn on the evidence of the climate change effect in the historical rainfall series."

Bohm (2012) notes "South Central Europe is among the spatially densest regions in terms of early instrumental climate data," citing Auer *et al*. (2007). He states this allows for successfully testing for homogeneity and developing "a larger number of very long instrumental climate time series at monthly resolution than elsewhere," which he thus proceeds to do. He notes the resulting long time series subset of the greater alpine region provides great potential for analyzing high frequency variability from the preindustrial (and mostly naturally forced) period to the "anthropogenic climate" of the past three decades. He reports "the unique length of the series in the region allowed for analyzing not less than 8 (for precipitation 7) discrete 30-year 'normal periods' from 1771–1800 to 1981–2010."

Bohm concludes "the overwhelming majority of seasonal and annual sub-regional variability trends is not significant." In the case of precipitation, he writes, "there is a balance between small but insignificant decreases and increases of climate variability during the more than 200 years of the instrumental period," and in the case of temperature he reports "most of the variability trends are insignificantly decreasing." In a "special analysis" of the recent 1981–2010 period that may be considered the first "normal period" under dominant greenhouse-gas-forcing, he finds all extremes "remaining well within the range of the preceding ones under mainly natural forcing." He notes "in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable."

Bohm, an Austrian researcher at the Central Institute for Meteorology and Geodynamics in Vienna, concludes there is "clear evidence that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region [GAR], and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period."

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7.6.4 North America

Cronin *et al*. (2000) studied salinity gradients across sediment cores extracted from Chesapeake Bay, the largest estuary in the United Sates, in an effort to determine precipitation variability in the surrounding watershed over the prior millennium. They discovered a high degree of decadal and multidecadal variability in moisture conditions over the 1,000-year period, with regional precipitation totals fluctuating by between 25% and 30%, often in extremely rapid shifts occurring over about a decade. They also determined precipitation was generally greater over the past two centuries than over the eight previous centuries, with the exception of a portion of the Medieval Warm Period (AD 1250–1350) when the climate was extremely wet. In addition, they found the region surrounding Chesapeake Bay had experienced several "megadroughts" lasting 60–70 years, some of which the researchers say "were more severe than twentieth century droughts."

Across the continent, Haston and Michaelsen (1997) developed a 400-year history of precipitation for 29 stations in coastal and near-interior California between San Francisco Bay and the U.S.-Mexican border using tree-ring chronologies. Their work revealed "region-wide precipitation during the last 100 years has been unusually high and less variable compared to other periods in the past."

Watanabe *et al*. (2001) analyzed delta $^{18}O/^{16}O$ and Mg/Ca ratios in cores obtained from a coral in the Caribbean Sea to examine seasonal variability in sea surface temperature and salinity during the Little Ice Age. They found sea surface temperatures during this period were about 2°C colder than they are currently, and sea surface salinity exhibited greater variability than it does now, indicating during the Little Ice Age "wet and dry seasons were more pronounced."

Zhang *et al*. (2001) analyzed the spatial and temporal characteristics of extreme precipitation events for the period 1900–1998 in Canada, using what they describe as "the most homogeneous long-term dataset currently available for Canadian daily precipitation." The evidence indicated decadal-scale variability was a dominant feature of both the frequency and intensity of extreme precipitation events, but it provided "no evidence of any significant long-term changes" in these indices during the twentieth century. The authors' analysis of precipitation totals (extreme and non-extreme) revealed a slightly increasing trend across Canada during the period of study, but it was found to be due to increases in the number of non-heavy precipitation events. Consequently, the researchers conclude "increases in the concentration of atmospheric greenhouse gases during the twentieth century have not been associated with a generalized increase in extreme precipitation over Canada."

Tian *et al*. (2006) derived a high-resolution $\delta^{18}O$ record of endogenic calcite obtained from sediments extracted from Steel Lake (46°58'N, 94°41'W) in north-central Minnesota, USA. They found "the region was relatively dry during the Medieval Climate Anomaly (~1400–1100 AD) and relatively wet during the Little Ice Age (~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods." Most striking, they found "drought variability was anomalously low during the 20th century"—so low that "~90% of the variability values during the last 3100 years were greater than the 20th-century average."

Gray *et al*. (2004) used cores extracted from 107 piñon pines at four different sites in the Uinta Basin Watershed of northeastern Utah to develop a proxy record of annual (June to June) precipitation spanning the period AD 1226–2001. They report "single-year dry events before the instrumental period tended to be more severe than those after 1900," and decadal-scale dry events were longer and more severe prior to 1900 as well. They note "dry events in the late 13th, 16th, and 18th centuries surpass the magnitude and duration of droughts seen in the Uinta Basin after 1900." At the other end of the spectrum, they report the twentieth century contained two of the strongest wet intervals (1938–1952 and 1965–1987), representing the seventh and second most intense wet regimes, respectively, of the record.

Rasmussen *et al*. (2006) earlier had demonstrated "speleothems from the Guadalupe Mountains in southeastern New Mexico are annually banded, and variations in band thickness and mineralogy can be used as a record of regional relative moisture (Asmerom and Polyak, 2004)." In their present work, they continued this tack, concentrating on "two columnar stalagmites collected from Carlsbad Cavern (BC2) and Hidden Cave (HC1) in the Guadalupe Mountains."

The three researchers report "both records, BC2 and HC1, suggest periods of dramatic precipitation variability over the last 3000 years, exhibiting large shifts unlike anything seen in the modern record." They also note the time interval of AD 900–1300 coincides with the well-known Medieval Warm Period and "shows dampened precipitation variability and overall drier conditions" "consistent with the idea of more frequent La Niña events and/or negative PDO phases causing elevated aridity in the region during this time." They say the preceding and following colder centuries "show increased precipitation variability ... coinciding with increased El Niño flooding events."

Clearly, moisture extremes in North America much greater than those observed in the modern era have occurred. Recent trends are neither unusual nor manmade; they are simply a normal part of Earth's natural climatic variability. North America is like Africa, Asia, and Europe: Precipitation variability in the Current Warm Period is no greater than what was experienced in earlier times.

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7.7 Storms

Among the highly publicized changes in weather phenomena predicted to attend CO_2-induced global warming are increases in the frequency and severity of various types of storms. Storms are a concern for the residents of any coastal city, as high winds, water surges, and high-energy waves can cause damage via flooding and erosion. It is therefore important to examine the historical records of storms for trends, to see if the so-named unprecedented rise in atmospheric CO_2 and temperature of the late twentieth and early twenty-first century has had any measurable effect on such storms.

Section 7.7 begins with an analysis of all types of storms by region (Sections 7.7.1.1 through 7.7.1.5), followed by a review of a specific type of storm (Dust Storms, Section 7.7.2) and three phenomena often associated with extreme storms (Hail, Section 7.7.3; Tornadoes, Section 7.7.4; and Wind, Section 7.7.5).

7.7.1 Regional Trends

For the globe as a whole, in its most recent *Assessment Report* the IPCC states "over the last century there is low confidence of a clear trend in storminess due to inconsistencies between studies or lack of long-term data in some parts of the world (particularly in the Southern Hemisphere)," adding "a reduction in the occurrence of Northern Hemisphere extratropical storms is likely, although, the most intense storms reaching Europe will likely increase in the strength" (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012).

The subsections of Section 7.7.1 examine what scientists have learned empirically about historic storm trends in an effort to understand how their past behavior has changed in relation to past temperatures. The results of that examination indicate storm frequency and intensity will not increase as a result of global warming.

7.7.1.1 Australia/New Zealand

De Lange and Gibb (2000) analyzed trends in sea-level data from several tide gauges located within Tauranga Harbor, New Zealand over the period 1960–1998. In an examination of seasonal, interannual, and decadal distributions of storm surge data, the two researchers identified a considerable decline in the annual number of storm surge events in the latter half of the nearly four-decade-long record. A similar trend also was noted in the magnitude of storm surges; and maximum water levels, including tides, also declined over the past two decades. Additionally, the authors found decadal variations in the data were linked to both the Interdecadal Pacific Oscillation (IPO) and the El Niño/Southern Oscillation (ENSO), such that La Niña events were associated with more storm surge days than El Niño events. Wavelet analyses of annual storm surge frequency data suggested before 1978 the frequency "was enhanced by the IPO, and subsequently it has been attenuated."

Similar findings were reported a decade later by Page *et al*. (2010) who, working with sediment cores extracted from Lake Tutira on the eastern end of New Zealand's North Island, developed a much longer 7,200-year history of the frequency and magnitude of storm activity, based on analyses of sediment grain size, diatom, pollen, and spore types and concentrations, carbon and nitrogen concentrations, and tephra and radiocarbon dating.

The ten New Zealanders plus one U.S. researcher report "the average frequency of all storm layers is one in five years," but "for storm layers ≥ 1.0 cm thick, the average frequency is every 53 years." Over the course of their record, they state, "there are 25 periods with an increased frequency of large storms," the onset and cessation of which "was usually abrupt, occurring on an inter-annual to decadal scale." They also note the duration of these stormy periods "ranged mainly from several decades to a century," but "a few were up to several centuries long," and "intervals between stormy periods range from about thirty years to a century." In addition, they find millennial-scale cooling periods tend to "coincide with periods of increased storminess in the Tutira record, while warmer events match less stormy periods."

Page *et al*. comment there is growing concern, driven by climate models, that global warming may cause abrupt changes in various short-term meteorological phenomena, "when either rapid or gradual forces on components of the Earth system exceed a threshold or tipping point." Their research shows the sudden occurrence of a string of years, or even decades, of unusually large storms is something that can happen at almost any time on its own, or at least without being driven by human activities such as the burning of fossil fuels.

Hayne and Chappell (2001) studied a series of storm ridges deposited over the past 5,000 years at Curacoa Island on the central Queensland shelf (18°40'S; 146°33'E), Australia, to create a history of major cyclonic events that have affected the area. They find "cyclone frequency was statistically constant over the last 5,000 years" and report "no indication that cyclones have changed in intensity." They also note isotopic and trace element evidence from ancient corals indicate sea surface temperatures were about 1°C warmer about 5,000 years ago, and pollen spectra from lake sediments suggest rainfall at that time was about 20% higher than today. These results clearly indicate, at least for this location, that cyclone frequency and intensity do not respond to changes in temperature as climate models have predicted.

Alexander *et al*. (2011) point out "understanding the long-term variability of storm activity would give a much better perspective on how unusual recent climate variations have been." They note "for southeast and eastern Australia some studies have been able to assess measures of storm activity over longer periods back to the 19th century (e.g., Alexander and Power, 2009; Rakich *et al*., 2008), finding either a decline in the number of storms or reduction in the strength of zonal geostrophic wind flow," although these studies "were limited to the analysis of only one or two locations."

The four researchers analyzed storminess across southeast Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century, finding "strong evidence for a significant reduction in intense wind events across SE Australia over the past century." They note "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease," while "in terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Yu *et al*. (2012) write "strong storms including cyclones, hurricanes, typhoons and strong wind events have catastrophic impacts on coral reefs worldwide," noting "Yu *et al*. (2004) suggested that the surface ages of well-preserved transported coral blocks could indicate the ages of past storm occurrences." This inference, they state, "was further confirmed by the analysis of sedimentation rates and grain sizes of lagoon sediments from the same reef (Yu *et al*., 2006; Yu *et al*., 2009)."

Yu *et al*. (2012) sampled 102 individual coral colonies (coral blocks) and four reef blocks they found distributed across the northern reef flat of Heron Reef, precisely dating them via the thermal ionization mass spectrometry (TIMS) U-series method, to explore their utility as indicators of historical storm activities around the southern end of the Great Barrier Reef, an area frequently visited by cyclones and storms, as noted by Done (1993) and Puotinen (2004). Based on the age distribution and relative probability frequency analysis of the dated coral and reef blocks, the seven scientists determined "there were eight relatively stormy periods since AD 1900, i.e., 1904–1909, 1914–1916, 1935–1941, 1945–1960, 1965–1967, 1976–1977, 1983–1988 and 2001–2007." Their yearly plot of the data clearly shows the very center of the twentieth century (1935–1965) to have been that century's most sustained stormy period in the vicinity of Heron Reef.

Li *et al*. (2011), citing "unprecedented public concern" with respect to the impacts of climate change, set out to examine the variability and trends of storminess for the Perth, Australia metropolitan coast. They conducted an extensive set of analyses using observations of wave, wind, air pressure, and water level over the period 1994–2008. The results of their analysis, in their view, would serve "to validate or invalidate the climate change hypothesis" that rising CO_2 concentrations are increasing the frequency and severity of storms.

As shown in Figure 7.7.1.1.1, all storm indices showed significant interannual variability over the period of record, but "no evidence of increasing (decreasing) trends in extreme storm power was identified to validate the wave climate change hypotheses for the Perth region."

In spite of what the Intergovernmental Panel on Climate Change has characterized as unprecedented global warming over the past two decades, Perth (Australia) has not experienced an increase in storm frequency or intensity. The studies cited above give little reason to believe CO_2-induced global warming will lead to increases in the frequency and magnitude of storms. Such claims are ungrounded in the peer-reviewed literature and have no basis in real-world observations.

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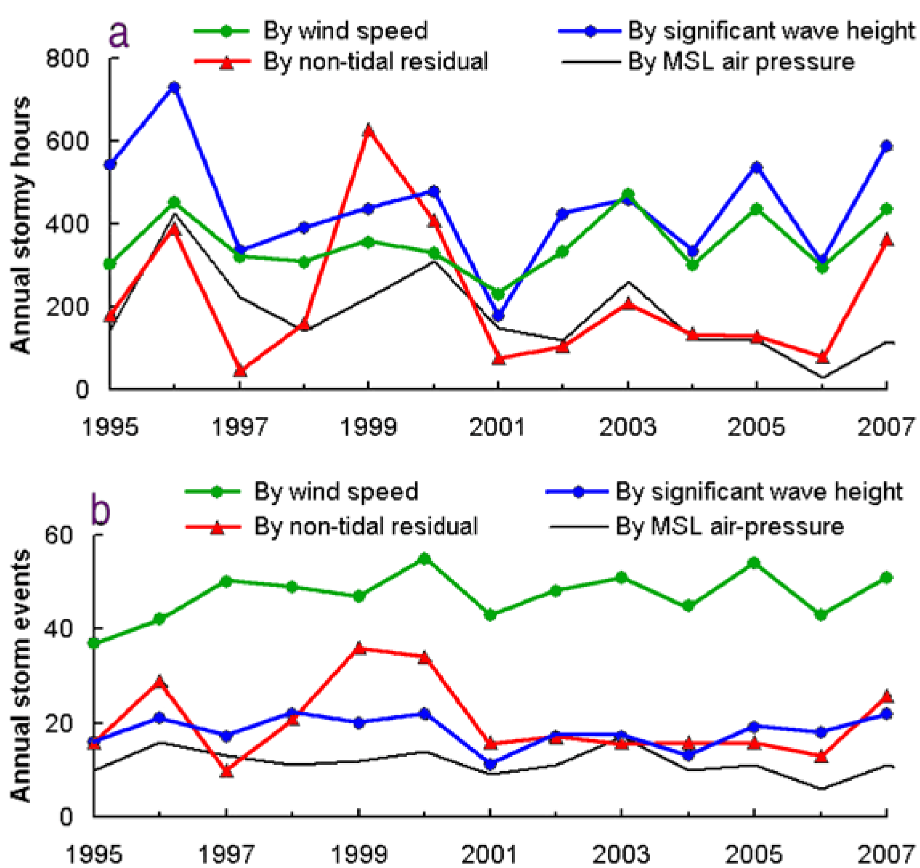

Figure 7.7.1.1.1. Annual storm trends for Perth, Australia defined by (a) stormy hours and (b) number of storm events, as determined by wind speed, significant wave height, non-tidal residual water level, and mean sea level pressure. Adapted from Li, F., Roncevich, L., Bicknell, C., Lowry, R., and Ilich, K. 2011. Interannual variability and trends of storminess, Perth, 1994–2008. *Journal of Coastal Research* **27**: 738–745.

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7.7.1.2 Europe

7.7.1.2.1 France

With respect to extreme weather events, Dezileau *et al*. (2011) write the major question of the day is, “are they linked to global warming or are they part of natural climate variability?” They say “it is essential to place such events in a broader context of time, and trace the history of climate changes over several centuries,” because “these extreme events are inherently rare and therefore difficult to observe in the period of a human life.”

Dezileau *et al*., nine researchers from France, analyzed regional historical archives and sediment cores extracted from two Gulf of Aigues-Mortes lagoons in the northwestern part of the occidental Mediterranean Sea for bio- and geo-indicators of past storm activities there, assessing “the frequency and intensity of [extreme] events during the last 1500 years” as well as “links between past climatic conditions and storm activities.” The analysis showed evidence of four “catastrophic storms of category 3 intensity or more,” which occurred at approximately AD 455, 1742, 1848, and 1893. “Taking into account text description of the 1742 storm,” they conclude it was “of category more than 4 in intensity,” and all four of the storms “can be called superstorms.”

Dezileau *et al*. make a point of noting “the apparent increase in intense storms around 250 years ago lasts to about AD 1900,” whereupon “intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD).” They add, “interestingly, the two periods of most frequent superstorm strikes in the Aigues-Mortes Gulf (AD 455 and 1700–1900) coincide with two of the coldest periods in Europe during the late Holocene (Bond cycle 1 and the latter half of the Little Ice Age.)” The authors suggest “extreme storm events are associated with a large cooling of Europe,” and they calculate the risk of such storms occurring during that cold period “was higher than today by a factor of 10,” noting “if this regime came back today, the implications would be dramatic.”

Clarke *et al*. (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, finding dune formation was generally most common during cooler climatic intervals. In the most recent of these cold periods, the authors note there is voluminous historical evidence of many severe North Atlantic wind storms in which the southward spread of sea ice and polar water likely created "an increased thermal gradient between 50°N and 65°N which intensified storm activity in the North Atlantic ... which may well have mobilized sand inland from the coast." In addition, they note sand-drift episodes across Europe "show synchroneity with sand invasion in the Aquitaine region of southwest France, implying a regional response to increased storminess." Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Working with historical accounts as well as "sedimentology, granulometry and faunistic data" obtained from two cores of the Pierre Blanche lagoon just south of Montpellier, France, Sabatier *et al*. (2008) found evidence of "washover events" that allowed them "to identify the strongest storms in the Mediterranean area" over the past four centuries. The eight researchers found "evidence of three main storms," which they identified as occurring in 1742, 1839, and 1893, all of which were deemed to have been much stronger than any of the twentieth century. A storm that occurred in 1982, which they describe as having been "the most recent catastrophic event," was not even "registered" in the lagoon sediment cores. Such a decline in the occurrence of "superstorms" in the Mediterranean area is a significant observation running counter to the model-based claim that global warming intensifies storms and brings more of them.

Sorrel *et al*. (2009) say studies indicate "estuarine systems are particularly sensitive to changing hydrological conditions," and one of the major purposes of examining them has been to determine "the effects of past centennial- to millennial-scale natural climatic fluctuations" in order to "better predict the impact of present-day and forthcoming climatic changes (and/or anthropogenic activities) on estuary infill." Of "crucial impact," in their estimation, "is the impact of storminess within warmer and colder periods on sedimentary patterns through the climatic regulation of (i) coastal wave hydrodynamics and (ii) continental inputs from the Seine river catchment area [in the case of their specific study] during the late Holocene."

Sorrel *et al*. linked high-resolution sediment and rock properties of materials found in cores collected from the Seine estuary in northwest France to climatic conditions of the past few thousand years. The five French researchers found "increased removal and transport of estuarine sediments occurred when winter storm activity greatly intensified over northwestern France," and they report on "four prominent centennial-scale periods of stronger storminess, occurring with a pacing of ~1500 years," which they say are "likely to be related to the last four [of] Bond's [1997, 2001] Holocene cold events," the most recent of which was the Little Ice Age, when Sorrel *et al*. say tidal and open marine hydrodynamics exerted "primary control on the sedimentary evolution of the system during 1200–2003 AD." In contrast, they found "the preservation of sedimentary successions in the outer Seine estuary was maximal during ca. 800–1200 AD," which they identify as the Medieval Warm Period, when they say "sediment reworking by waves was considerably reduced."

Sorrel *et al*. (2010) conducted a similar analysis for the macrotidal Bay of Vilaine (47°20'–47°35'N, 2°50'–2°30'W). Their results indicated "the late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives," where the authors found "an increase in the contribution of riverine inputs occurred during the MWP [Medieval Warm Period]" at "times of strong fluvial influences in the estuary during ca. 880–1050 AD." They also report "preservation of medieval estuarine flood deposits implies that sediment remobilization by swells considerably waned at that time, and thus that the influence of winter storminess was minimal," in accordance with the findings of Proctor *et al*. (2000) and Meeker and Mayewski (2002). Furthermore, they state the preservation of fine-grained sediments during the Middle Ages has been reported in other coastal settings, citing the studies of Chaumillon *et al*. (2004) and Billeaud *et al*. (2005). They note, "all sedimentary records from the French and Spanish Atlantic coasts" suggest "the MWP appears to correspond to a period of marked and recurrent increases in soil erosion with enhanced transport of suspended matter to the shelf as a result of a likely accelerated human land-use development," adding "milder climatic conditions during ca. 880–1050 AD may have favored the preservation of estuarine flood deposits in estuarine sediments through a waning of winter storminess, and, thus, reduced coastal hydrodynamics at subtidal depths."

Sorrell *et al*. (2010) also note the upper successions of the sediment cores "mark the return to more energetic conditions in the Bay of Vilaine, with coarse sands and shelly sediments sealing the medieval clay intervals," while observing "this shift most probably documents the transition from the MWP to the Little Ice Age," which led to the "increased storminess both in the marine and continental ecosystems (Lamb, 1979; Clarke and

Rendell, 2009)" associated with "the formation of dune systems over a great variety of coastal environments in northern Europe: Denmark (Aagaard *et al*., 2007; Clemmensen *et al*., 2007, 2009; Matthews and Briffa, 2005), France (Meurisse *et al*., 2005), Netherlands (Jelgersma *et al*., 1995) and Scotland (Dawson *et al*., 2004)." In what they call an even "wider perspective," they note the Medieval Warm Period "is recognized as the warmest period of the last two millennia (Mayewski *et al*., 2004; Moberg *et al*., 2005)."

The French scientists conclude "the preservation of medieval estuarine flood deposits implies that sediment reworking by marine dynamics was considerably reduced between 880 and 1050 AD," implying "climatic conditions were probably mild enough to prevent coastal erosion in northwestern France."

Pirazzoli (2000) analyzed tide-gauge, wind, and atmospheric pressure data over the period 1951–1997 for the northern portion of the Atlantic coast of France. The author notes atmospheric depressions (storms) and strong surge winds "are becoming less frequent" in this region and "ongoing trends of climate variability show a decrease in the frequency and hence the gravity of coastal flooding" over the period of study. Such findings should be "reassuring," Pirazzoli notes, especially for those concerned about coastal flooding.

The studies described above suggest there has been no significant increase in the frequency or intensity of stormy weather in France as Earth recovered from the global chill of the Little Ice Age. Storminess in most other parts of the planet also decreased over this period, as described in other subsections, suggesting there is no real-world, data-driven reason to believe storms would get any worse or become more frequent if Earth were to warm somewhat more in the future.

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7.7.1.2.2 United Kingdom

Allan *et al*. (2009) point out an analysis of a 47-year storm database by Alexander *et al*. (2005) "showed an increase in the number of severe storms in the 1990s in the United Kingdom," but "it was not possible to say with any certainty that this was either indicative of climatic change or unusual unless it was seen in a longer-term context." Allan *et al*. extended the database of Alexander *et al*. back to 1920, almost doubling the length of the record, after which they reanalyzed the expanded dataset for the periods of boreal autumn (October, November, December) and winter (January, February, March). They determined both databases exhibited peaks in storminess in the 1920s and 1990s, with boreal autumn storms being more numerous in the 1920s and winter storms being more numerous in the 1990s. The total storm numbers for each decade are plotted in Figure 7.7.1.2.2.1 As can be seen there, both the beginning and end decades of the record experienced nearly identical numbers of storms, demonstrating the increasingly greater number of extreme storms affecting the British Isles from the 1960s through the 1990s likely was not related to the global warming of that period.

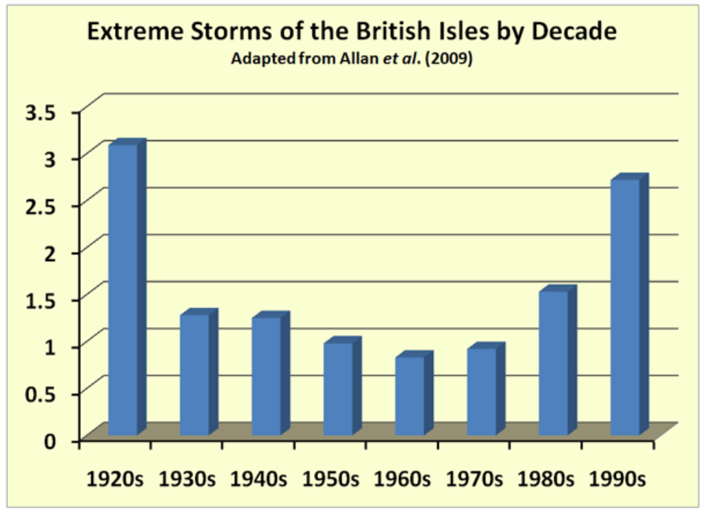

Figure 7.7.1.2.2.1. Number of extreme storms impacting the British Isles in each of eight decadal periods. Created from results reported by Allan, R., Tett, S., and Alexander, L. 2009. Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present. *International Journal of Climatology* **29**: 357–371.

Dawson *et al*. (2002) searched daily meteorological records from northern and northwestern Scotland—Stornoway (Outer Hebrides), Lerwick (Shetland Islands), Wick (Caithness), and Fair Isle (west of the Shetland Islands)—for data pertaining to gale-force winds over the period 1876–1996, which they used to construct a history of storminess for that period. Although North Atlantic storminess and associated wave heights were found to have increased over the prior two decades, storminess in the North Atlantic region "was considerably more severe during parts of the nineteenth century than in recent decades." In addition, whereas the modern increase in storminess appeared to be associated with a spate of substantial positive values of the North

Atlantic Oscillation (NAO) index, Dawson *et al.* state "this was not the case during the period of exceptional storminess at the close of the nineteenth century." During that earlier period, the conditions that fostered modern storminess were apparently overpowered by something even more potent; i.e., cold temperatures, which the authors say led to an expansion of sea ice in the Greenland Sea that expanded and intensified the Greenland anticyclone, which in turn led to the North Atlantic cyclone track being displaced farther south. Additional support for this view is provided by the hypothesis of Clarke *et al*. (2002), who postulated that a southward spread of sea ice and polar water results in an increased thermal gradient between 50°N and 65°N that intensifies storm activity in the North Atlantic and supports dune formation in the Aquitaine region of southwest France.

These studies suggest the increased storminess and wave heights observed in the European sector of the North Atlantic Ocean over the past two decades are not the result of global warming, but rather are associated with the most recent periodic increase in the NAO index. A longer historical perspective reveals North Atlantic storminess was even more severe than it is now during the latter part of the nineteenth century, when it was significantly colder than it is now. The storminess of that much colder period was so great it was actually decoupled from the NAO index. Hence, the long view of history suggests the global warming of the past century or so has led to an overall decrease in North Atlantic storminess.

Tide-gauge data also have been utilized as proxies for storm activity in England. Based on high-water measurements made at the Liverpool waterfront over the period 1768–1999, Woodworth and Blackman (2002) found the annual maximum surge-at-high-water declined at a rate of 0.11 ± 0.04 meters per century, suggesting the winds responsible for producing high storm surges were much stronger and/or more common during the early part of the record (colder Little Ice Age) than the latter part (Current Warm Period).

Focusing on a well-studied and data-rich 16-km-long section of the Sefton coastline of northwest England, Esteves *et al*. (2011) used the longest available measured datasets from the eastern Irish Sea and beyond—including tide levels, surge heights, wind speeds, and wave heights—in a search for evidence of long-term changes in the metocean climate. They analyzed data defining the rate of change in shoreline position at the study site derived from a range of historical maps and aerial photographs for the period 1894–2005, with the primary aim of assessing "whether temporal changes in the rates and magnitudes of coastal erosion can be attributed to the observed trends in metocean data, and if these trends can, in turn, be associated with climate change."

According to the three UK researchers, their results "show no evidence of enhanced storminess or increases in surge heights or extreme water levels," and "the evolution of the coastline analyzed at various temporal scales shows no strong connection with metocean trends." With the exception of mean monthly wind speed (which trended slightly upwards at one site and slightly downwards at another), the authors report the available metocean data "do not indicate any statistically significant changes outside seasonal and decadal cycles."

Dawson *et al*. (2004a) examined the sedimentary characteristics of a series of Late Holocene coastal windstorm deposits found on the Scottish Outer Hebrides, an island chain that extends across the latitudinal range 56–58°N. These deposits form part of the landward edges of coastal sand accumulations that are intercalated with peat, the radiocarbon dating of which was used to construct a local chronology of the windstorms. This work revealed "the majority of the sand units were produced during episodes of climate deterioration both prior to and after the well-known period of Medieval warmth." The researchers also say "the episodes of sand blow indicated by the deposits may reflect periods of increased cyclogenesis in the Atlantic associated with increased sea ice cover and an increase in the thermal gradient across the North Atlantic region." In addition, they report "dated inferred sand drift episodes across Europe show synchroneity with increased sand mobilization in SW France, NE England, SW Ireland and the Outer Hebrides, implying a regional response to storminess with increased sand invasion during the cool periods of the Little Ice Age," citing the corroborative studies of Lamb (1995), Wintle *et al*. (1998), Gilbertson *et al*. (1999), and Wilson *et al*. (2001).

Dawson *et al*. (2004b) examined 120- to 225-year records of gale-days per year from five locations across Scotland, northwest Ireland, and Iceland, which they compared with a much longer 2,000-year record for the same general region. They found four of the five century-scale records showed a greater frequency of storminess in the cooler 1800s and early 1900s than throughout the remainder of the warmer twentieth century. "Considered over the last ca. 2000 years," they report, "it would appear that winter storminess and climate-driven coastal erosion was at a minimum during the Medieval Warm Period," just the opposite of what climate models typically predict; i.e., more storminess with warmer temperatures.

Throughout a vast portion of the North Atlantic Ocean and adjacent Europe, storminess and wind strength appear to have been inversely related to mean global air temperature over most of the past two millennia, with the most frequent and intense events occurring both prior to and following the Medieval Warm Period. The model-based claim that Europe will experience more intense and frequent windstorms if air temperatures continue to rise fails to resonate with reality.

Although some studies suggest there has been a recent increase in storminess across the United Kingdom, others have shown that as Earth has recovered from the global chill of the Little Ice Age, there has been no significant increase in either the frequency or intensity of stormy weather in this area. In fact, most studies suggest just the opposite.

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7.7.1.2.3 Other Regions

Bielec (2001) analyzed thunderstorm data from Cracow, Poland, for the period 1896–1995, finding an average of 25 days of such activity per year, with a non-significant linear-regression-derived increase of 1.6 storm days from the beginning to the end of the record. From 1930 onward, the trend was negative, revealing a similarly derived decrease of 1.1 storm days. In addition, there was a decrease in the annual number of thunderstorms with hail over the entire period and a decrease in the frequency of storms producing precipitation in excess of 20 mm.

Similar findings were reported by the same author two years later (Bielec-Bakowska, 2003) for thunderstorm occurrences at seven Polish synoptic weather stations (Hel, Szczecin, Koszalin, Poznan, Wroclaw, Raciborz, and Krakow) over the period 1885–2000. In this second study the University of Silesia scientist determined "over an annual period of 116 years, no clear trends of changes in the number of days with thunderstorms in Poland were found," noting also "interannual variability of days with thunderstorms in individual seasons did not show any specific trend," except in the winter season, and then only for Szczecin, Krakow, and Koszalin. These findings led her to state "the analysis did not unequivocally confirm the opinion that the number of thunderstorms in the cold part of the year increases," and "a similar phenomenon was observed in the whole of Europe."

With the perspective of anthropogenic climate change, Barring and von Storch (2004) point out, the occurrence of extreme events such as windstorms may "create the perception that ... the storms lately have become more violent, a trend that may continue into the future." Intending to test this inference, and relying on data rather than perception to address the topic, the two researchers analyzed long time series of pressure readings for Lund (since 1780) and Stockholm (since 1823), Sweden, analyzing the annual number of pressure observations below 980 hPa, the annual number of absolute pressure tendencies exceeding 16 hPa/12h, and intra-annual 95th and 99th%iles of the absolute pressure differences between two consecutive observations. They determined the storminess time series they developed "are remarkably stationary in their mean, with little variations on time scales of more than one or two decades." For example, they note "the 1860s–70s was a period when the storminess indices showed general higher values," as was the 1980s–1990s, but subsequently, "the indices have returned to close to their long-term mean."

Barring and von Storch conclude their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." During "the entire historical period," storminess was "remarkably stable, with no systematic change and little transient variability."

Noting "a great amount of evidence for changing storminess over northwestern Europe is based on indirect data and reanalysis data rather than on station wind data," Smits *et al*. (2005) investigated trends in storminess over the Netherlands based on hourly records of 10-m wind speed observations made at 13 meteorological stations across the country with uninterrupted records for the time period 1962–2002. They report "results for moderate wind events (that occur on average 10 times per year) and strong wind events (that occur on average twice a year) indicate a decrease in storminess over the Netherlands [of] between 5 and 10% per decade."

Raicich (2003) analyzed 62 years of sea-level data for the period 1 July 1939 to 30 June 2001 at Trieste, in the Northern Adriatic, to determine historical trends of surges and anomalies. This work revealed no definite trends in weak and moderate positive surges, while strong positive surges clearly became less frequent, even in the face of a gradually rising sea level, "presumably," in the words of Raicich, "as a consequence of a general weakening of the atmospheric activity," also found to have been the case for Brittany (France) by Pirazzoli (2000).

Barredo (2010) examined large historical windstorm event losses in Europe over the period 1970–2008 for 29 European countries. After adjusting the data for "changes in population, wealth, and inflation at the country level and for inter-country price differences using purchasing power parity," the researcher, employed by the Institute for Environment and Sustainability, European Commission-Joint Research Centre in Ispra, Italy, reported "the analyses reveal no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure," adding "increasing disaster losses are overwhelmingly a consequence of changing societal factors."

Additional evidence for the recent century-long decrease in storminess in and around Europe comes from Bijl *et al*. (1999), who analyzed long-term sea-level records from several coastal stations in northwest Europe. They report, "although results show considerable natural variability on relatively short (decadal) time scales," there is "no sign of a significant increase in storminess ... over the complete time period of the data sets." In the southern portion of the North Sea, where natural variability was more moderate, they found a trend, but it was "a tendency towards a weakening of the storm activity over the past 100 years."

Stoffel *et al*. (2005) note debris flows are a type of mass movement that frequently causes major destruction in alpine areas; since 1987, they report, there had been an apparent above-average occurrence of such events in the Valais region of the Swiss Alps, prompting some researchers to suggest the increase was the result of global warming (Rebetez *et al*., 1997). Stoffel *et al*. used dendrochronological methods to determine whether the recent increase in debris-flow events was indeed unusual, and if so whether it made sense to attribute the increase to CO_2-induced global warming.

In extending the history of debris-flow events (1922–2002) back to the year 1605, they found "phases with accentuated activity and shorter recurrence intervals than today existed in the past, namely after 1827 and until the late nineteenth century." The nineteenth century period of high-frequency debris flow was shown to coincide with a period of higher flood activity in major Swiss rivers, and less frequent debris flow activity after 1922 corresponded with lower flooding frequencies. Debris flows from extremely large mass movement events, similar to what occurred in 1993, were found to have "repeatedly occurred" in the historical past, and to have been of such substantial magnitude that, in the opinion of Stoffel *et al*., the "importance of the 1993 debris-flow surges has to be thoroughly revised."

Stoffel *et al*.'s work demonstrates the apparent above-average number of debris flow events since 1987 was only that—apparent. They report debris flows occurred "ever more frequently in the nineteenth century than they do today." They conclude, "correlations between global warming and modifications in the number or the size of debris-flow events, as hypothesized by, e.g., Haeberli and Beniston (1998), cannot, so far, be confirmed in the study area."

These findings clearly demonstrate the importance of evaluating the uniqueness of Earth's contemporary climatic state—or the uniqueness of recent trends in various climate-related phenomena—over a much longer timespan than just the past century or, even worse, merely a portion of it. Only when a multicentennial or millennial view of the subject is available can one adequately evaluate the uniqueness of a climate-related phenomenon's recent behavior, let alone link that behavior to late twentieth century or early twenty-first century global warming.

Other studies reveal important conclusions with respect to trends in storminess when examining a timescale much longer than 100 years. Ogrin (2007) presented "an overview of severe storms and a reconstruction of periods with their reiterative occurrence in sub-Mediterranean Slovenia in the warm half of the year during the so-called pre-instrumental period," based on "data gathered in secondary and tertiary historical sources." Speaking of "violent storms" and "the periods in which these phenomena were more frequent and reached, as to the costs of damage caused, the level of natural disasters or even catastrophes," Ogrin reports "the 17th and 18th centuries were undoubtedly such periods, particularly their first halves, when besides storms also some other weather-caused natural disasters occurred quite often, so that the inhabitants, who mainly depended on the self-subsistent agriculture, could not recover for several years after some consecutive severe rigours of the weather." In addition, he reports "the frequency of violent storms in that time was comparable to the incidence towards the end of the 20th century."

Ogrin, who is in the Department of Geography of the University of Ljubljana, writes the late twentieth century increase in violent storms "is supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere." However, he reports "the damage done by severe storms in the past does not differ significantly from the damage in the present." This suggests the weather extremes of today, which he says are "supposed to be a human-generated consequence of emitting greenhouse gasses and of the resulting global warming of the atmosphere," may in fact be caused by something else, for if they have occurred in the past for a different reason (and they have), they can be occurring today for a different reason too.

Clarke and Rendell (2009) also recognized "an understanding of the patterns of past storminess is particularly important in the context of future anthropogenically driven climate change," especially in light of "predictions of increased storm frequency ... by the end of the current century." They reviewed evidence for storm activity across the North Atlantic region derived from instrumental records and archival evidence of storm impacts, which they then compared to sedimentological and chronological evidences of sand movement and dune building along western European coasts.

The two UK researchers determined "the most notable Aeolian sand drift activity was concentrated in the historic period 0.5–0.1 ka (AD 1500–1900) which spans the Little Ice Age." They state "within this period, low solar activity, during the Maunder (AD 1645–1715) and Dalton (AD 1790–1830) Minima, has been related to changes in Atlantic storm tracks (van der Schrier and Barkmeijer, 2005), anomalously cold winter and summer temperatures in Scandinavia (Bjerknes, 1965), and the repositioning of the polar front and changing sea ice cover (Ogilive and Jonsson, 2001)." In addition, they state "the Holocene record of sand drift in western Europe includes episodes of movement corresponding to periods of Northern Hemisphere cooling (Bond *et al*., 1997) ... and provides the additional evidence that these periods, like the Little Ice Age, were also stormy," further suggesting any future global warming would more likely result in less, rather than more, storminess in that part of the planet.

Based on optically stimulated luminescence (OSL) dating of the coastal sediment succession, Riemann *et al*. (2011) established "a detailed and reliable chronology" of the Swina barrier at the southern end of the Baltic Sea, two sandy spits or depositional landforms (Wolin and Uznam) that extend outward from the seacoast. This sediment history revealed much about the climate history of the region. Following the Roman Warm Period, which the five researchers say “is known for a moderate and mild climate in Europe” that produced brown foredunes, there was a hiatus between the brown and yellow dunes from 470 AD to 760 AD that “correlates with a cold and stormy period that is known as the Dark Ages Cold Period,” which they say “is well known as a cooling event in the climatic records of the North Atlantic (Bond *et al*., 1997; McDermott *et al*., 2001) and in marine sediment cores from Skagerrak (Hass, 1996),” and which also was associated with a phase of increased aeolian activity in northeast England reported by Wilson *et al*. (2001).

Next, as expected, came the Medieval Warm Period. And finally, Riemann *et al*. write, “the cold and stormy Little Ice Age (Hass, 1996) correlates to the formation of the transgressive white dune I in the sediment successions, which were dated to between 1540 and 1660 AD.” They note, “the Little Ice Age is documented in North and West Europe in plenty of coastal dunefields, and resulted in sand mobilisation and development of transgressive dunes (e.g., Clemmensen *et al*., 2001a,b, 2009; Wilson *et al*., 2001, 2004; Clarke *et al*., 2002; Ballarini *et al*., 2003; Clemmensen and Murray, 2006; Aagaard *et al*., 2007; Sommerville *et al*., 2007; Clarke and Rendell, 2009),” due to a colder climate and increased storminess related to periodic shifts of the North Atlantic Oscillation (Dawson *et al*., 2002).

Noting “the systematic accretion of foredunes is accompanied by a moderate climate and a progressive plant cover,” the German and Polish scientists say foredune instability is “related to aeolian sand mobilisation within phases of a decreased plant cover caused by colder and stormier conditions.” These numerous sets of dune-derived data clearly demonstrate that in this particular part of the world warming brings less storminess.

Remarking that “the Mediterranean region is one of the world’s most vulnerable areas with respect to global warming,” citing Giorgi (2006), Sabatier *et al*. (2012) produced a high-resolution record of paleostorm events along the French Mediterranean coast over the past 7,000 years. According to the nine French scientists, their work “recorded seven periods of increased storm activity at 6300–6100, 5650–5400, 4400–4050, 3650–3200, 2800–2600, 1950–1400, and 400–50 cal yr BP.” They associate the latter interval with the Little Ice Age. “In contrast,” they state, their results show “the Medieval Climate Anomaly (1150–650 cal yr BP) was characterized by low storm activity.” In addition, they note these changes in coastal hydrodynamics were in phase with those observed over the Eastern North Atlantic by Billeaud *et al*. (2009) and Sorrel *et al*. (2009), and the periods of increased storminess they identified seem to correspond to periods of Holocene cooling detected in the North Atlantic by Bond *et al*. (1997, 2001), together with decreases in sea surface temperature reported by Berner *et al*. (2008), who they also say “associated this high frequency variation in sea surface temperature with ^{14}C production rates, implying solar-related changes are an important underlying mechanism for the observed ocean climate variability.”

Sabatier *et al*. conclude “whatever the ultimate cause of these millennial-scale Holocene climate variations, the main decreases of sea surface temperature observed in the North Atlantic seem to be an important mechanism to explain high storm activity in the NW Mediterranean area.” Their together with those of the others they cite, suggest if Earth’s climate continues to warm, for whatever reason, storm activity in the Northwest Mediterranean area will likely significantly subside.

Barring and Fortuniak (2009) point out “extra-tropical cyclone frequency and intensity are currently under intense scrutiny because of the destruction recent windstorms have brought to Europe.” They note “several studies using reanalysis data covering the second half of the 20th century suggest increasing storm intensity in the northeastern Atlantic and European sector.” They analyzed the “inter-decadal variability in cyclone activity over northwestern Europe back to AD 1780 by combining information from eight storminess indices applied in a Eulerian framework,” indices that “use the series of thrice-daily sea level pressure observations at Lund and Stockholm” in Scandinavia.

The two Swedish scientists say their results show former reanalysis studies “cover a time period chiefly coinciding with a marked, but not exceptional in our 225-year perspective, positive variation in the regional cyclone activity that has more recently reversed,” noting “because of the inter-decadal variations, a near-centennial time perspective is needed when analyzing variations in extra-tropical cyclone activity and the associated weather conditions over northwestern Europe.” By taking this more long-term approach, the two researchers found “there is no significant overall long-term trend common to all indices in cyclone activity in the North Atlantic and European region since the Dalton minimum"; "the marked positive trend beginning around 1960 ended in the mid-1990s and has since then reversed"; and "this positive trend was more an effect of a 20th-century minimum in cyclone activity around 1960, rather than extraordinary high values in [the] 1990s."

Clemmensen *et al*. (2007) examined sedimentological and geomorphological properties of the dune system on the Danish island of Anholt, finding "the last aeolian activity phase on Anholt (AD 1640–1900) is synchronous with the last part of the Little Ice Age." The team of researchers further note "dune stabilization on Anholt seems to a large degree to have been natural, and probably records a decrease in storminess at the end of the 19th century and the beginning of the 20th century," and this timing "is roughly simultaneous with dunefield stabilization on the west coast of Jutland and on Skagen Odde," citing the work of Clemmensen and Murray (2006).

Bjorck and Clemmensen (2004) extracted cores of peat from two raised bogs in the near-coastal part of southwest Sweden, from which they derived histories of wind-transported clastic material via systematic counts of quartz grains of various size classes that enabled them to calculate temporal variations in Aeolian Sand Influx (ASI), which has been shown to be correlated with winter wind climate in that part of the world. They found "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," and "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

The two researchers also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they state an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)." They also find high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting this period coincides with the Sporer Minimum of AD 1420–1530. In addition, they note the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

The two researchers also report degree of humification (DOH) intervals "correlate well with the classic late-Holocene climatic intervals," which they specifically state to include the Modern Climate Optimum (100–0 cal. yr BP), the Little Ice Age (600–100 cal. yr BP), the Medieval Warm Period (1250–600 cal. yr BP), the Dark Ages Cold Period (1550–1250 cal. yr BP), and the Roman Climate Optimum (2250–1550 cal. yr BP). There would thus appear to be little doubt that winter storms throughout southern Scandinavia were more frequent and intense during the multicentury Dark Ages Cold Period and Little Ice Age than during the Roman Warm Period, Medieval Warm Period, and Current Warm Period, providing strong evidence to refute the contention that storminess tends to increase during periods of greater warmth.

As Earth has recovered from the global chill of the Little Ice Age, there appears to have been no significant increase in either the frequency or intensity of stormy weather in many regions across Europe. Most studies suggest just the opposite. There is no real-world or data-driven reason to believe storms would necessarily get any worse or become more frequent if Earth were to warm somewhat more in the future.

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7.7.1.3 North America

7.7.1.3.1 Canada

Recognizing "media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe weather events," Hage (2003) set out to test this hypothesis in the prairie provinces of Alberta and Saskatchewan in western Canada. The author utilized "previously unexploited written resources such as daily and weekly newspapers and community histories" to establish a database adequate for determining long-term trends of all destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) for the region over the period 1882–2001. Hage notes because "sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns, … extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors." Hage found "all intense storms showed no discernible changes in frequency after 1940."

Lawson (2003) examined the occurrence of blizzards at a number of locations within the Prairie Ecozone of western Canada, analyzing trends in occurrence and severity over the period 1953–1997. No significant trends were found in central and eastern locations. In the western prairie locations, the author found a significant downward trend in blizzard frequency, noting "this trend is consistent with results found by others that indicate a decrease in cyclone frequency over western Canada." He also notes the blizzards that do occur "exhibit no trend in the severity of their individual weather elements." These observed trends "serve to illustrate that the changes in extreme weather events anticipated under Climate Change may not always be for the worse."

Gascon *et al*. (2010) conducted a study they describe as "the first to document the climatology of major cold-season precipitation events that affect southern Baffin Island." They examined the characteristics and climatology of the 1955–2006 major cold-season precipitation events at Iqaluit, the capital of Nunavut, located on the southeastern part of Baffin Island in the northwestern end of Frobisher Bay, basing their work on analyses of hourly surface meteorological data obtained from the public archives of Environment Canada. The precipitation data were corrected to account for gauge catchment errors due to wind effects, snow-water equivalence variations, and human error in the manually retrieved precipitation data for the period 1955–1996; the remaining data were used in their uncorrected state.

The three researchers detected a non-significant decrease in autumn and winter storm activity over the period of their study, which they say comports with the results of Curtis *et al.* (1998), who observed a concomitant decrease in annual precipitation in the western Arctic. This was true in spite of the findings of Zhang *et al*. (2004), who Curtis *et al.* say "reported an increase in cyclonic activity over the past fifty years, as well as McCabe *et al*. (2001), Wang *et al*. (2004) and Yin (2005)," who reported a northward shift in such activity. That shift apparently was not great enough to "translate into major precipitation events, or at least not in Iqaluit," as revealed by the authors' results depicted in Figure 7.7.1.3.1.1.

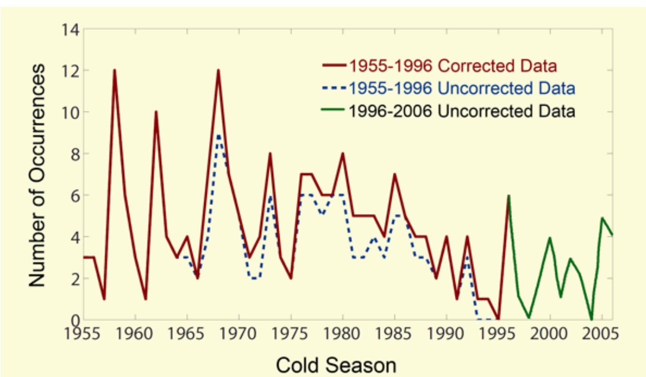

Figure 7.7.1.3.1.1. Cold-season occurrences of major precipitation events at Iqaluit, Nunavut, Canada. Adapted from Gascon, G., Stewart, R.E., and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327–337.

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7.7.1.3.2 Alaska

Hudak and Young (2002) examined the number of fall (June–November) storms in the southern Beaufort Sea region based on criteria of surface wind speed for the relatively short period of 1970–1995. Although there was considerable year-to-year variability in the number of storms, there was no discernible trend over the 26-year period in this region of the globe, where climate models predict the effects of CO_2-induced global warming to be most evident.

Mason and Jordan (2002) studied numerous depositional environments along the tectonically stable, unglaciated eastern Chuckchi Sea coast that stretches across northwest Alaska, deriving a 6,000-year record of sea-level change. They learned "in the Chukchi Sea, storm frequency is correlated with colder rather than warmer climatic conditions." Consequently, they say their data "do not therefore support predictions of more frequent or intense coastal storms associated with atmospheric warming for this region."

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7.7.1.3.3 Eastern USA

Zhang *et al*. (2000) used ten long-term records of storm surges derived from hourly tide gauge measurements to calculate annual values of the number, duration, and integrated intensity of storms in this region. Their analysis did not reveal any trends in storm activity during the twentieth century, which they say is suggestive of "a lack of response of storminess to minor global warming along the U.S. Atlantic coast during the last 100 yr."

Similar results were reported by Boose *et al*. (2001), who examined historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They discerned "no clear century-scale trend in the number of major hurricanes." For the most recent and reliable 200-year portion of the record, however, the cooler nineteenth century had five of the highest-damage F3 category storms, whereas the warmer twentieth century had only one such storm.

Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York between 1851 and 2005 to assess the degree of likelihood that twentieth century global warming might be influencing these storms. According to the author, "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and of these storms, "14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms." For Long Island in particular, he further reports "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." He found storm activity was greatest in the late nineteenth century and late twentieth century, and "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century." Vermette thus concludes, "rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century."

Noren *et al*. (2002) extracted sediment cores from 13 small lakes distributed across a 20,000-km^2 region of Vermont and eastern New York. They found "the frequency of storm-related floods in the northeastern United States has varied in regular cycles during the past 13,000 years (13 kyr), with a characteristic period of about 3 kyr." The most recent upswing in storminess did not begin with what the IPCC calls the unprecedented warming of the twentieth century, but "at about 600 yr BP [Before Present], coincident with the beginning of the Little Ice Age." The authors conclude the increase in storminess was likely a product of natural changes in the Arctic Oscillation.

Mallinson *et al*. (2011) employed optically stimulated luminescence (OSL) dating of inlet-fill and flood tide delta deposits from locations in the Outer Banks barrier islands of North Carolina to provide a "basis for understanding the chronology of storm impacts and comparison to other paleoclimate proxy data" in the region over the past 2,200 years. Analyses of the cores revealed "the Medieval Warm Period (MWP) and Little Ice Age (LIA) were both characterized by elevated storm conditions as indicated by much greater inlet activity relative to today." They write, "given present understanding of atmospheric circulation patterns and sea-surface temperatures during the MWP and LIA, we suggest that increased inlet activity during the MWP responded to intensified hurricane impacts, while elevated inlet activity during the LIA was in response to increased nor'easter activity." The group of five researchers state their data indicate, relative to climatic conditions of the Medieval Warm Period and Little Ice Age, there has more recently been "a general decrease in storminess at mid-latitudes in the North Atlantic," reflecting "more stable climate conditions, fewer storm impacts (both hurricane and nor'easter), and a decrease in the average wind intensity and wave energy field in the mid-latitudes of the North Atlantic."

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7.7.1.3.4 Central and Southern USA

Bove *et al*. (1998) studied land-falling hurricanes whose eyes crossed the coast between Cape Sable, Florida and Brownsville, Texas between 1896 and 1995, finding the first half of the twentieth century had more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. The same is true for intense hurricanes of category 3 on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes have been trending downward since 1966, with the decade starting in 1986 exhibiting the fewest intense hurricanes of the century.

Liu and Fearn (1993) studied major storms along the U.S. Gulf Coast over the past 3,500 years. Using sediment cores taken from the center of Lake Shelby in Alabama, they determined "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years," with the last of these superstorms occurring around 700 years ago. They further note "climate modeling results based on scenarios of greenhouse warming predict a 40%–50% increase in hurricane intensities in response to warmer tropical oceans." If one of these severe storms (about a century overdue) were to hit the Alabama coast, it would be nothing more than an illustration of the age-old adage that history repeats itself.

Muller and Stone (2001) examined historical data relating to tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island, Texas to Cape Hatteras, North Carolina for the 100-year period 1901–2000. Their analysis revealed the temporal variability of tropical storm and hurricane strikes was "great and significant," with most coastal sites experiencing "pronounced clusters of strikes separated by tens of years with very few strikes." The data did not support the claim of a tendency for increased storminess during warmer El Niño years; for tropical storms and hurricanes together, the authors found an average of 1.7 storms per El Niño season, 2.6 per neutral season, and 3.3 per La Niña season. For hurricanes only, the average rate of occurrence ranged from 0.5 per El Niño season to 1.7 per La Niña season.

Daoust (2003) suggested using tornado days instead of tornado frequencies "provides a more stable data set which should allow a more accurate analysis of the phenomenon." Daoust catalogued daily tornado frequencies for each county of Missouri, USA, for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state's 115 counties, its six climatic divisions, and the entire state. Results indicated the presence of positive trends in the tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant, but negative. At the state level, Daoust reports "for the last 53 years, no long-term trend in tornado days can be found."

Changnon (2001) compared thunderstorm activity at both an urban and rural location in Chicago to determine whether there might be an urban influence on thunderstorm activity. Over the 40-year period investigated (1959–1998), he found the urban station experienced an average of 4.5 (12%) more thunderstorm days per year than the more rural station, and statistical tests revealed this difference to be significant at the 99% level in all four seasons of the year. This finding should elicit further caution in interpreting storm trend studies, many of which are based on data obtained from urban locations, which in the case of thunderstorms in Chicago, skewed the observational data upwards.

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7.7.1.3.5 Conterminous USA

Hayden (1999) investigated storm frequencies between 25° and 55°N latitude and 60° and 125°W longitude from 1885 to 1996. Over this 112-year period, he reports, large regional changes in storm occurrences were observed, but when integrated over the entire geographic area, no net change in storminess was evident.

Similar results were noted by Changnon and Changnon (2000), who examined hail-day and thunder-day occurrences over the 100-year period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the country. They found the frequency of thunder-days peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Thereafter, both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence decreased to only 65% of what it was at mid-century, accompanied by a drop in national hail insurance losses over the same period.

Several years later, the authors conducted an analysis of snowstorms. Changnon and Changnon (2006) point out "global climate models predict that more weather extremes will be a part of a changed climate due to greenhouse gases," and such a climate change "is anticipated to result in alterations of cyclone activity over the Northern Hemisphere (Lawson, 2003)." They also note "a change in the frequency, locations, and/or intensity of extratropical cyclones in the mid-latitudes would alter the incidence of snowstorms," citing the work of Trenberth and Owen (1999).

The authors conducted "a climatological analysis of the spatial and temporal distributions of ... damaging snowstorms and their economic losses … using property-casualty insurance data that consist of highly damaging storm events, classed as catastrophes by the insurance industry, during the 1949–2000 period." In support of this approach to the subject, they report the National Academy of Sciences has identified insurance catastrophe data as "the nation's best available loss data (National Research Council, 1999)."

The father-and-son research team reports "the incidence of storms peaked in the 1976–1985 period," but snowstorm incidence "exhibited no up or down trend during 1949–2000," although national monetary losses did have a significant upward time trend indicative of "a growing societal vulnerability to snowstorms." The two researchers conclude, "the temporal frequency of damaging snowstorms during 1949–2000 in the United States does not display any increase over time, indicating that either no climate change effect on cyclonic activity has begun, or if it has begun, altered conditions have not influenced the incidence of snowstorms."

Schwartz and Schmidlin (2002) compiled a database of blizzards for the years 1959–2000 for the conterminous United States. A total of 438 blizzards were identified in the 41-year record, yielding an average of 10.7 blizzards per year. Year-to-year variability was significant, with the number of annual blizzards ranging from a low of 1 in the winter of 1980–1981 to a high of 27 during the winter of 1996–1997. Linear regression analysis revealed a statistically significant increase in the annual number of blizzards during the 41-year period; the total area affected by blizzards each winter remained relatively constant and showed no trend. If these observations are both correct, then average blizzard size is much smaller now than it was four decades ago. As the authors note, however, "it may also be that the NWS is recording smaller, weaker blizzards in recent years that went unrecorded earlier in the period, as occurred also in the official record of tornadoes in the United States."

The work of Schwartz and Schmidlin suggests the frequency of U.S. blizzards may have increased, but intensity likely decreased. Alternatively, the authors suggest the reported increase in blizzard frequency may be due to an observational bias that developed over the years, for which there is a known analogue in the historical observation of tornadoes. That this possibility is likely a probability is suggested by the study of Gulev *et al*. (2001), who analyzed trends in Northern Hemispheric winter cyclones over essentially the same time period (1958–1999) and found a statistically significant decline of 1.2 cyclones per year using NCEP/NCAR reanalysis pressure data.

Balling and Cerveny (2003) reviewed the scientific literature to determine what has been learned from United States weather records about severe storms during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense precipitation, tornadoes, hurricanes, and winter storm activity. They report several scientists have identified an increase in heavy precipitation, but "in other severe storm categories, the trends are downward."

Kunkel (2003) reports a sizable increase in the frequency of extreme precipitation events in the United States since the 1920s and 1930s, but notes the frequencies of the late 1800s and early 1900s were about as high as those of the 1980s and 1990s, which suggests there may have been no century-long increase in this type of extreme weather.

Changnon (2003a) utilized a newly available extensive dataset on thunderstorm days covering the period 1896–1995 to assess long-term temporal variations in thunderstorm activity at 110 first-order weather reporting stations across the United States. By dividing the data into five 20-year segments, Changnon found "the 1936–1955 period was the nation's peak of storm activity during the 100-year period ending in 1995." During this central 20-year period, 40% of the 110 first-order weather stations experienced their greatest level of storm activity, whereas during the final 20-year period from 1976–1995, only 15% of the stations experienced their greatest level of storm activity.

In a separate paper, Changnon (2003b) investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States, finding mixed results. For example, he reports "one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms)." As mentioned earlier, however, had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon likely would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

Insurance losses, by contrast, rose rapidly over the past several decades, Changnon found, the primary reason being "a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society's vulnerability." When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events "do not exhibit an upward trend." Thus, as Changnon emphasizes, "the adjusted loss values for these extremes [do] not indicate a shift due to global warming." He reiterates these real-world observations "do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO_2 levels, that call for weather extremes and storms to increase in frequency and intensity."

Similar findings with respect to monetary loss trends due to extreme storm events were reported again by Changnon three years later in two separate papers.

In the first of these papers, working with data from the insurance industry, the researcher from the Illinois State Water Survey analyzed "catastrophes caused solely by high winds" that had had their losses adjusted so as to make them "comparable to current year [2006] values" (Changnon, 2009a). Although the average monetary loss of each year's catastrophes "had an upward linear trend over time, statistically significant at the 2% level," when the number of each year's catastrophes was considered, "low values occurred in the early years (1952–1966) and in later years (1977–2006)," and "the peak of incidences came during 1977–1991." Thus it was not surprising, as Changnon describes it, that "the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend."

In his second paper from 2009, Changnon (2009b) utilized "records of extremely damaging storms in the United States during the years 1949–2006 … to define their temporal distribution," where such storms were defined as those producing losses greater than \$100 million, with a special subset defined as those producing losses greater than \$1 billion. At this extreme level of classification it was clearly evident "the number of storms at both loss levels has increased dramatically since 1990." The author presents four possible explanations for his findings. First, he notes "storm measurement and data collection have improved over time." Second and third, he says "the increases may also reflect natural variations in climate or a shift in climate due to global warming." He then states "a fourth reason is that society has become more vulnerable to storm damages."

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7.7.1.4 Other Regions

Sorrel *et al*. (2012) note the southern coast of the English Channel in northwestern France is "well suited to investigate long-term storminess variability because it is exposed to the rapidly changing North Atlantic climate system, which has a substantial influence on the Northern Hemisphere in general." They present "a reappraisal of high-energy estuarine and coastal sedimentary records," finding "evidence for five distinct periods during the Holocene when storminess was enhanced during the past 6,500 years."

The six scientists say "high storm activity occurred periodically with a frequency of about 1,500 years, closely related to cold and windy periods diagnosed earlier (Bond *et al*., 2001; Wanner *et al*., 2008; Wanner *et al*., 2011)." They show "millennial-scale storm extremes in northern Europe are phase-locked with the period of internal ocean variability in the North Atlantic of about 1,500 years (Debret *et al*., 2009)," with the last extreme stormy period "coinciding with the early to mid-Little Ice Age." They note "in contrast, the warm Medieval Climate Optimum was characterized by low storm activity (Sorrel *et al*., 2009; Sabatier *et al*., 2012)." Sorrel *et al*. conclude, "in light of concerns about the impact of anthropogenic greenhouse gases on extreme storm events in the coming years/decades, our results indicate that modern coupled ocean-atmosphere dynamics at North Atlantic mid-latitudes should tend towards the low phase of the 1,500-year internal oceanic cycle, in contrast to Little Ice Age climate conditions," which suggests warming should lead to relatively less storminess, contrary to what the models project.

Gulev *et al*. (2001) utilized sea-level pressure from NCEP/NCAR reanalysis data for the period 1958–1999 to develop a winter (January–March) climatology of cyclones (storms) for the Northern Hemisphere, from which they statistically analyzed only those cyclones that reached a sea-level pressure of 1000 mb or lower. They found the yearly mean number of winter cyclones for the period was 234, although there was pronounced interannual and spatial variability in the record. Linear trend estimates indicated a statistically significant (95% level) annual decline of 1.2 cyclones per year, suggesting there were 50 fewer cyclones in the Northern Hemisphere winter at the end of the record than there were 42 years prior (Figure 7.7.1.4.1). Additional data analyses suggest Northern Hemisphere winter cyclones are intensifying at quicker rates and are reaching greater maximum depths (lower sea-level pressure) at the end of the record than they were at the beginning of the record. However, the wintertime cyclones are also experiencing shorter life cycles, dissipating more quickly at the end of the record than at the beginning.

Winter storms in North America at the end of the

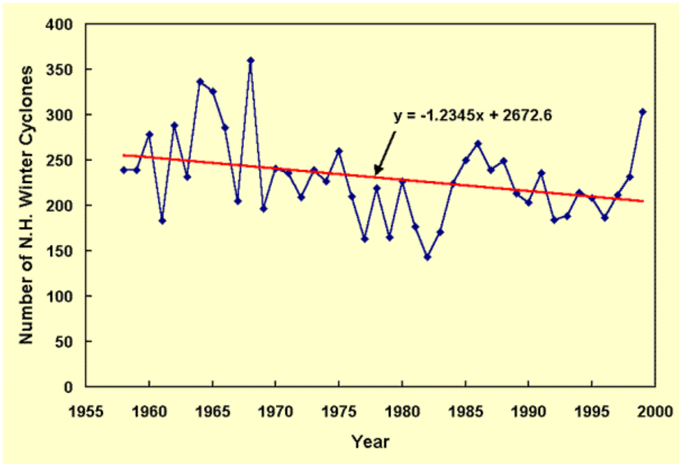

Figure 7.7.1.4.1. Yearly number of Northern Hemisphere cyclones over the period 1958-1999. Adapted from Gulev, S.K., Zolina, O., and Grigoriev, S. 2001. Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics* **17**: 795–809.

twentieth century thus appear to have been maturing faster but dissipating more quickly than they were four decades earlier. Could this change be the result of global warming? The authors say the phenomenon is probably connected to large-scale features of atmospheric variability, such as the North Atlantic Oscillation and the North Pacific Oscillation. As for the large decrease reported in the annual number of Northern Hemisphere cyclones over the 42-year period, this observation is in direct opposition to model-based extreme weather predictions, which suggest the frequency of such events will increase as a result of global warming.

Simmonds and Keay (2000) employed a new cyclone finding and tracking scheme to conduct what they say "is arguably the most reliable analysis of Southern Hemisphere cyclone variability undertaken to date." They found the annual average number of cyclones in the Southern Hemisphere steadily increased from the start of the assessment period. After peaking in 1972, however, there was an overall decline, and the authors state "the counts in the 1990s have been particularly low." They detected a small increase in mean cyclone radius, but they note this effect has only "served to partially offset the effect of the remarkable decrease in cyclone numbers." They also note the time series of Southern Hemisphere cyclone numbers shows an out-of-phase relationship with the Southern Hemisphere mean annual temperature record, which suggests, in their words, "that the downward trends in cyclone numbers are associated with a warming Southern Hemisphere."

Yu *et al*. (2004) point out, "according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones." Because "understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events," they devised a way to decipher the history of severe storms in the region of the southern South China Sea. At Youngshu Reef (9°32'–9°42'N, 112°52–113°04'E), they used standard radiocarbon dating and TIMS U-series dating to determine the times of occurrence of storms strong enough to "relocate" large *Porites* coral blocks widespread on the reef flats there. Yu *et al*. determined "during the past 1000 years, at least six exceptionally strong storms occurred," which they dated to approximately 1064 ± 30, 1218 ± 5, 1336 ± 9, 1443 ± 9, 1682 ± 7, and 1872 ± 15 AD, yielding an average recurrence frequency of 160 years. Although models typically suggest that storms will become more frequent and severe in response to global warming and the warming of the twentieth century was the most significant of the past millennium, none of the six severe storms identified by Yu *et al*. occurred during the past millennium's last century.

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7.7.1.5 Global

Although most studies focus on storms trends for a given location or region, some researchers have attempted to examine the trends for the globe as a whole. This section reviews that research.

Huntington (2006) states there is "a theoretical expectation that climate warming will result in increases in evaporation and precipitation, leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio *et al*., 1991; Loaciga *et al*., 1996; Trenberth, 1999; Held and Soden, 2000; Arnell *et al*., 2001)." He reiterates the long-held climate-model-derived notion that "an intensification of the water cycle may lead to changes in water-resource availability," meaning "floods and droughts," as well as "an increase in the frequency and intensity of tropical storms." He proceeds to explore these theoretical expectations via a review of the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, soil moisture, and other parameters.

"On a globally averaged basis," according to Huntington, "precipitation over land increased by about 2% over the period 1900–1998 (Dai *et al*., 1997; Hulme *et al*., 1998)." He also notes "an analysis of trends in world continental runoff from major rivers from 1910–1975 found an increase in runoff of about 3% (Probst and Tardy, 1987)," and a recent reanalysis of these trends for the period 1920–1995 "confirmed an increase in world continental runoff during the 20th century (Labat *et al*., 2004)."

These findings suggest global warming may indeed have intensified the global hydrologic cycle over the twentieth century. However, Huntington also reports "the empirical evidence to date does not consistently support an increase in the frequency or intensity of tropical storms and floods." As for droughts, he says the "evidence indicates that summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock *et al*., 2000)."

Thus there appears to have been a slight intensification of the hydrologic cycle throughout the twentieth century over Earth's land area, which may or may not have been caused by the concomitant warming of the globe, but it also appears there was no intensification of deleterious weather phenomena such as tropical storms, floods, and droughts. In addition, Smith *et al*. (2006) demonstrate over the period 1979–2004, when the IPCC claims the planet experienced a warming unprecedented over the past one to two millennia, there was no net change in global precipitation (over both land and water).

Gulev and Grigorieva (2004) analyzed ocean wave heights (a proxy for storms) using the Voluntary Observing Ship wave data of Worley *et al*. (2005) to characterize significant wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists report "the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950," which would seem to vindicate model projections of increasing storms. "However," they continue, "for the period 1885–2002 there is no secular trend in HS in the Atlantic" and "the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002."

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century "is comparable with that for recent decades," and "in the Atlantic it is even higher than during the last 5 decades." In the Atlantic the mean HS of the decade of the 1920s is higher than that of any recent decade, and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific it also appears the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes a definitive answer on this point. Nevertheless, it is clear that annual mean wave height (a proxy for storminess) over the last decade of the twentieth century was not higher than annual wave height values earlier in the century.

Key and Chan (1999) analyzed trends in seasonal and annual frequencies of low-pressure centers (cyclones) at 1000-mb (near-surface) and 500-mb heights for six latitude regions (0–30°N, 0–30°S, 30–60°N, 30–60°S, 60–90°N and 60–90°S) over the four-decade period 1958–1997, while also determining trends in cyclone frequencies for El Niño vs. La Niña years. They found both positive and negative trends (some significant and some not) in cyclone frequency at both atmospheric levels over the 40-year period. Cyclone frequencies at both atmospheric levels were also found to be lower at all latitude regions except two (30–60°S and 60–90°S) during El Niño years, as opposed to La Niña years. Although Key and Chan found some regional differences in cyclone frequencies, there was no indication of any global trend, positive or negative. They also found fewer cyclones occur during warmer El Niño years than during cooler La Niña years, appearing to further invalidate model-based claims that global warming will result in more storms globally..

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7.7.2 Dust Storms

Will dust storms increase in response to CO_2-induced global warming? That question requires an answer given model-based projections that both the frequency and intensity of extreme weather events will increase in the future.

According to Griffin *et al*. (2002), "as much as two billion metric tons of dust are lifted into the Earth's atmosphere every year," and soil particulates from Africa and Asia cross both the Atlantic and Pacific Oceans. As a result of the trans-Pacific transport, Wilkening *et al*. (2000) state "the once-pristine air above the North Pacific Ocean is polluted," and they go on to list several implications for a number of terrestrial and oceanic ecosystems. They also note we can expect these impacts to increase with economic expansion around the world, and by analogy we can infer such impacts have likely grown in tandem with population and industrialization over the past century or so. Griffin *et al*. remark dust storms originating in North Africa "routinely affect the air quality in Europe and the Middle East," and millions of tons of African sediment "fall on the North Amazon Basin of South America every year."

Prospero (2001) suggests nearly everyone in the United States living east of the Mississippi River is affected by dust of African origin. Likewise, Prospero and Lamb (2003) report measurements made from 1965 to 1998 in the Barbados trade winds show large interannual changes in the concentration of dust of African origin that are highly anticorrelated with the prior year's rainfall in the Soudano-Sahel, and they note the IPCC report of Houghton *et al*. (2001) "assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts." They say "there is little firm evidence to support either of these assumptions."

Griffin *et al*. report in April 2001 a large dust cloud originating over the Gobi Desert of China "moved eastward across the globe, crossing Korea, Japan, the Pacific (in five days), North America (causing sporadic reports of poor air quality in the United States), the Atlantic Ocean and then Europe."

Grousset *et al*. (2003) studied dust samples collected in the French Alps, analyzing their mineralogical and geochemical composition, including the isotopic composition of the neodymium contained in the minerals. They then reconstructed airmass backward trajectories from archived meteorological data, including corroboration by satellite imagery, and used a global transport model driven by assimilated meteorology to simulate dust deflation and long-range transport. Their work revealed one of the sets of dust samples came from North Africa, and the second set originated in the Takla-Makan desert of China. Their work additionally suggested the latter set of dust particles had traveled "more than 20,000 km in about two weeks, and along their journey, crossed China, the North Pacific, North America and then the North Atlantic Ocean." That knowledge, they write, "is important from the viewpoint of understanding the dust itself" as well as "the heavy metal, fungal, bacterial and viral pollution that may be associated with it."

Liu *et al*. (2004) analyzed trends in spring dust storm frequency for western and southwestern China-Mongolia for the period 1952–2003, finding both interannual and interdecadal trends throughout the 52-year period. By decade, the number of spring dust storms varied from 21 in the 1950s, to 44 in the 1960s, to a high of 60 in the 1970s, then back down to 35 in the 1980s, and a low of 25 in the 1990s. In addition, they determined strong and cold Siberian air masses enhance dust storm numbers, whereas weaker and warmer Siberian air masses lower them. Thus, if warming of the globe increases temperatures in the northern part of China and Mongolia, Liu *et al*. say "the China-Mongolia ridge will continue to rise and suppress Mongolian cyclones and dust storm activities in Western China-Mongolia."

Zhu *et al*. (2008) note "changes in occurrences of natural disasters, which are possibly associated with global warming, have been receiving ever-increasing attention world wide," and the "dust storm is one of the severe disastrous weather [phenomena] in China." In this regard, however, and in contrast to the general tenor of most model-based discussions of global warming and extreme weather, they write, "a number of studies have shown that the spring dust storm frequency (DSF) bears a negative correlation with the local surface air temperature, and exhibits a downward trend over the past 50 years," citing the studies of Qian *et al*. (2002), Zhou and Zhang (2003), Zhai and Li (2003), Zhao *et al*. (2004), Fan *et al*. (2006), and Gong *et al*. (2006, 2007).

Zhu *et al*. explored "the long-term variation of Chinese DSF in spring (March to May), and its possible linkage with the global warming and its related circulation changes in the Northern Hemisphere," using data from 258 stations within the region surrounding Lake Baikal (70–130°E, 45–65°N) over the period 1954 to 2007. The authors found a "prominent warming" in recent decades, as well as "an anomalous dipole circulation pattern" in the troposphere that "consists of a warm anti-cyclone centered at 55°N and a cold cyclone centered around

30°N," leading to "a weakening of the westerly jet stream and the atmospheric baroclinicity in northern China and Mongolian regions, which suppress the frequency of occurrence and the intensity of the Mongolian cyclones and result in the decreasing DSF in North China." Rising temperatures, therefore, served as the trigger mechanisms in trends in DSF, but not in the general manner projected by the IPCC: Rising temperatures reduced DSF instead of increasing it.

Lim *et al*. (2005) examined the eolian quartz content (EQC) of a high-resolution sedimentary core taken from Cheju Island, Korea, from which they produced a proxy record of major Asian dust events that reached the region over the past 6,500 years. This analysis indicated the EQC was relatively low 6,500–4,000 years BP, high 4,000–2,000 years BP, and low again from 2,000 years BP to the present, with the most recent 1,500 years BP being lower in EQC than any previous time in the record. The Asian dust time series also was found to contain significant millennial- and centennial-scale periodicities. Cross-spectral analysis between the EQC and proxy solar activity record showed significant coherent cycles at 700, 280, 210, and 137 years with nearly the same phase changes, leading the three researchers to conclude the centennial-scale periodicities in the EQC can be ascribed primarily to short-term fluctuations in solar activity.

Engelstaedter *et al*. (2003) used dust storm frequency (DSF) data from 2,405 stations represented in the International Station Meteorological Climate Summary as a surrogate measure of dust emissions to test the assumption that vegetation is an important control of dust emission at the global scale. To represent vegetation cover, they used two independent datasets: a satellite-derived distribution of actual vegetation types, and a model-derived distribution of potential natural vegetation. Employing these tools, they learned "the highest DSFs are found in areas mapped by DeFries and Townshend (1994) as bare ground," and "moderate DSFs occur in regions with more vegetation, i.e., shrubs & bare ground, and lowest DSFs occur in grasslands, forests, and tundra," where ground cover is highest. Thus they conclude "average DSF is inversely correlated with leaf area index (an index of vegetation density) and net primary productivity," suggesting whatever increases vegetative cover should reduce the severity of dust emissions from the soil beneath as well as the dust's subsequent transport to various parts of the world.

Evan *et al*. (2006) reached a similar conclusion, applying a new daytime over-water dust detection algorithm for the Advanced Very High Resolution Radiometer (AVHRR) to 24 years (1982–2005) of wintertime satellite imagery over West Africa and the surrounding Atlantic Ocean and comparing it with a similarly derived Normalized Difference Vegetation Index (NDVI) shown to be responsive to vegetation variability in the Sahel. A strong relationship was found to exist between tropical North Atlantic dustiness and the vegetation index, "suggesting the possibility that vegetation changes in the Sahel play an important role in variability of downwind dustiness." Evan *et al*. conclude "dust mobilization may be mediated by vegetation through increases in soil stability and reductions of wind stress on the surface, when more vegetation is present," which "would be consistent with the modeling studies of Gillette (1999) and Engelstaedter *et al*. (2003)."

Rising atmospheric CO_2 might play a valuable role in this regard. The well-documented increase in plant water use efficiency that results from increases in the air's CO_2 content should allow more plants to grow in the arid source regions of Earth's dust clouds, helping stabilize and shield the soil, decreasing its susceptibility to wind erosion and reducing the amounts of dust made airborne and transported by globe-girdling winds. Moreover, the propensity for elevated CO_2 concentrations to increase soil moisture content as a consequence of CO_2-induced reductions in plant transpiration should also encourage plant growth. And the ability of extra atmospheric CO_2 to enhance the growth of cryptobiotic soil crusts should directly stabilize the surface of the soil, even in the absence of higher plants. Direct support for the role of elevated CO_2 in increasing desert biomass is provided by the recent work of Donohue *et al*. (2013), who found foliage has increased over warm, dry regions by 5 to 10% from 1982 to 2010.

We conclude with a review of the findings of Piao *et al*. (2005), who used a "time series data set of Normalized Difference Vegetation Index (NDVI) obtained from the Advanced Very High Resolution Radiometer available from 1982 to 1999 (Tucker *et al*., 2001; Zhou *et al*., 2001), and precipitation and temperature data sets, to investigate variations of desert area in China by identifying the climatic boundaries of arid area and semiarid area, and changes in NDVI in these areas." They found "average rainy season NDVI in arid and semiarid regions both increased significantly during the period 1982-1999." The NDVI increased for 72.3% of total arid regions and for 88.2% of total semiarid regions, such that the area of arid regions decreased by 6.9% and the area of semiarid regions decreased by 7.9%. They also report that by analyzing Thematic Mapper satellite images, "Zhang *et al*. (2003) documented that the process of desertification in the Yulin area, Shannxi Province showed a decreased trend between 1987 and 1999," and "according to the national monitoring data on desertification in western China (Shi, 2003), the annual desertification rate decreased from 1.2% in the 1950s to -0.2% at present."

Noting "variations in the vegetation coverage of these regions partly affect the frequency of sand-dust storm occurrence (Zou and Zhai, 2004)," Piao *et al*. conclude "increased vegetation coverage in these areas will likely fix soil, enhance its anti-wind-erosion ability, reduce the possibility of released dust, and consequently cause a mitigation of sand-dust storms." And, as pointed out in previous studies, they report "recent studies have suggested that the frequencies of strong and extremely strong sand-dust storms in northern China have significantly declined from the early 1980s to the end of the 1990s (Qian *et al*., 2002; Zhao *et al*., 2004)."

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7.7.3 Hail

Insurance costs related to life and property damage caused by extreme weather events have been steadily rising in the United States and elsewhere, and it is not uncommon for many in the insurance industry and government to place the blame for this development on what they claim are significant increases in the frequencies and intensities of severe weather events, since climate models suggest these phenomena should be increasing as a consequence of CO_2-induced global warming. But is this explanation correct?

According to the latest IPCC report, there is "insufficient evidence" to determine whether such small-scale severe weather events as hail are changing in response to what they perceive to be the unprecedented modern rise in both atmospheric CO_2 and temperature (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The following research, however, strongly suggests changes in atmospheric CO_2 and temperature have exerted no measurable influence on hail trends, when hail data are properly analyzed.

After describing and analyzing property losses caused by a series of Midwestern U.S. hailstorms that occurred on 13–14 April 2006, totaling $1.822 billion, "an amount considerably more than the previous record high of $1.5 billion set by an April 2001 hail event," Changnon (2009) described and analyzed the "top ten" hail-loss events that occurred in the United States over the period 1950–2006, finding "an increase over time in [hail event] frequency and losses with most major events occurring since 1990."

These findings would appear to support the contention that global warming is causing more hail events. However, the Illinois State Water Survey researcher opines only "two factors could have affected this increase." One of them, in his words, could have been "more frequent occurrences of major cases of strong atmospheric instability, leading to the development of supercell thunderstorms capable of persisting for many hours, covering large areas, and producing large hailstones." He says this scenario "has not been measured and cannot be verified." The second factor, as he describes it, "is the expansion of the nation's metropolitan areas, enhancing the target for hail damages to property," in support of which he notes "urban population in the U.S. since 1960 increased by 56% and urban areas grew by 154%," according to the World Almanac (2008), making a good case for the second of the two factors Changnon suggests.

This latter explanation also was favored by Changnon in an earlier study (Changnon, 2003) in which he investigated trends in severe weather events and changes in societal and economic factors over the last half of the twentieth century. He found trends in various weather extremes over this period were mixed, noting, "one trend is upwards (heavy rains-floods), others are downward [including "hail, hurricanes, tornadoes, and severe thunderstorms"], and others are unchanging flat trends (winter storms and wind storms)." As for why U.S. insurance losses due to most extreme weather events rose so rapidly throughout the past several decades, Changnon reports "the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society's vulnerability."

Further support for this thesis comes from the even earlier work of Kunkel *et al*. (1999), who analyzed historical trends in several different types of extreme weather events, together with their societal impacts, near the close of the last century. They found most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses. However, they found "trends in most related weather and climate extremes do not show comparable increases with time." These observations led them to conclude the increasing economic losses "are primarily due to increasing vulnerability arising from a variety of societal changes," and in this regard they found "increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors."

When the temporal span of analysis is expanded even further, the claim that global warming is increasing hail events is completely debunked. Changnon and Changnon (2000), for example, analyzed hail-day and thunder-day occurrences over the century-long period 1896–1995 in terms of 20-year averages obtained from records of 66 first-order weather stations distributed across the United States. This effort revealed thunder-day frequency peaked in the second of the five 20-year intervals, and hail-day frequency peaked in the third or middle interval. Both parameters declined to their lowest values of the century in the final 20-year period. Hail-day occurrence fell to only 65% of what it had been at mid-century, dropping so low there was a decline in national hail insurance losses over the final two decades of the study.

Locations beyond the United States yield similar results. Bielec (2001) analyzed thunderstorm data obtained at Cracow, Poland, described as possessing "one of the few continuous records in Europe with an intact single place of observation and duration of over 100 years." Over the length of this record, there were 2,470 days with thunderstorms, an average of about 25 days per year. The highest annual number of thunderstorm days was 37, recorded in 1968 and again in 1975, and the lowest annual number was 9, in 1904. Close analysis of the data revealed a slight but non-significant linear increase of 1.6 storms per year from the beginning to the end of the record. From 1930 onward, however, the trend is negative, revealing a linear decrease of 1.1 storms per year. With respect to the annual number of thunderstorms with hail, Bielec reports there was a decrease over the hundred-year period.

From a historical hail dataset of 753 stations compiled by the National Meteorological Information Center of China, which "includes hail data for all weather stations in the surface meteorological observational network over the whole of China from 1951 to 2005," Xie *et al*. (2008) "chose 523 stations with complete observations from 1960 to 2005" to study "annual variations and trend[s] of hail frequency across mainland China during 1960–2005."

As is evident in Figure 7.7.3.1, Xie *et al*. found "no trend in the mean Annual Hail Days (AHD) from 1960 to [the] early 1980s but a significant decreasing trend afterwards." This downturn was concomitant with a warming of the globe the IPCC claims was unprecedented over the past one to two millennia, leading the three authors to conclude global warming may actually imply "a possible reduction of hail occurrence."

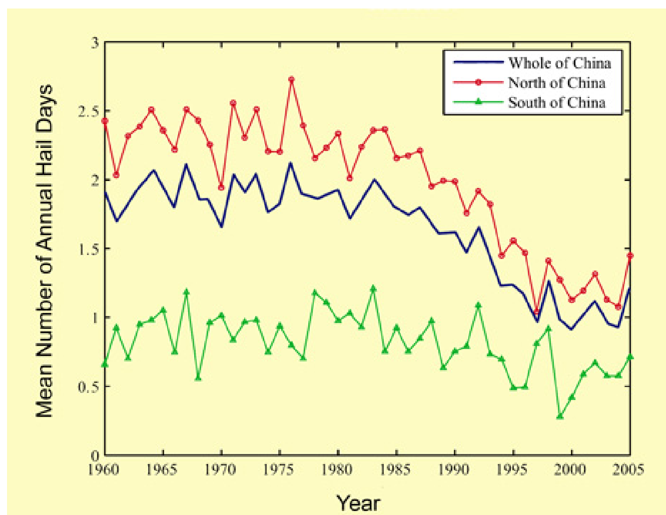

Figure 7.7.3.1. Mean Annual Hail Day variations and trends in northern China, southern China, and the whole of China. Adapted from Xie, B., Zhang, Q., and Wang, Y. 2008. Trends in hail in China during 1960–2005. *Geophysical Research Letters* **35**: 10.1029/2008GL034067.

Recognizing Xie *et al*. (2008) found a "significant decreasing trend of hail frequency in most of China from the early 1980s based on 46 years of data during 1960-2005," Xie and Zhang (2010) set out to learn whether there also had been any change in another type of extremeness (hailstone size), noting "changes in hail size are also an important aspect of hail climatology." They examined the long-term trend of hail size in four regions of China over the period 1980–2005, using maximum hail diameter data obtained from the Meteorological Administrations of Xinjiang Uygur Autonomous Region (XUAR), Inner Mongolia Autonomous Region (IMAR), Guizhou Province, and Hebei Province.

The researchers found an uptrend in maximum hail diameter in Hebei, a flat trend in XUAR, and a slight downtrend in both Guizhou and IMAR, but "none of the trends is statistically significant."

These results, combined with the other findings presented above, demonstrate global warming, CO_2-induced or otherwise, likely has had nothing to do with the increasing damages caused by extreme weather events in general. It also has had no tendency to increase the occurrence of hail storms, at least in the United States, China, and portions of Poland for which pertinent data have been properly analyzed.

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7.7.4 Tornadoes

According to the latest IPCC report, there is "insufficient evidence" to determine whether small-scale severe weather events such as tornadoes are changing in response to what the IPCC perceives to be an unprecedented rise in both atmospheric CO_2 and temperature of the modern era (p. 14 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). The research reviewed below, however, , strongly suggests changes in CO_2 and temperature have exerted no measurable influence on tornado trends. Because tornadoes often occur in conjunction with other severe storm events, other features of severe storms are frequently mentioned in the studies discussed below.

In a review of "temporal fluctuations in weather and climate extremes that cause economic and human health impacts," Kunkel *et al*. (1999) analyzed empirical data related to historical trends of several different types of extreme weather events and their societal impacts. This work revealed "most measures of the economic impacts of weather and climate extremes over the past several decades reveal increasing losses." However, they found "trends in most related weather and climate extremes do not show comparable increases with time," suggesting "increasing losses are primarily due to increasing vulnerability arising from a variety of societal changes, including a growing population in higher risk coastal areas and large cities, more property subject to damage, and lifestyle and demographic changes subjecting lives and property to greater exposure." Regarding tornado losses, they specifically state "increasing property losses due to thunderstorm-related phenomena (winds, hail, tornadoes) are explained entirely by changes in societal factors."

Balling and Cerveny (2003) also reviewed the scientific literature to determine what had been learned about severe storms in the United States during the modern era of greenhouse gas buildup in the atmosphere, paying particular attention to thunderstorms, hail events, intense precipitation, tornadoes, hurricanes, and winter storm activity. They found several scientists had identified an increase in heavy precipitation, but "in other severe storm categories, the trends are downward," just the opposite of what climate models contend should be the case.

Noting "media reports in recent years have left the public with the distinct impression that global warming has resulted, and continues to result, in changes in the frequencies and intensities of severe weather events," with these changes implied as being mostly for the worse, Hage (2003) used "previously unexploited written resources such as daily and weekly newspapers and community histories" to establish a database adequate for determining long-term trends of destructive windstorms (primarily thunderstorm-based tornadoes and downbursts) in the prairie provinces of Alberta and Saskatchewan in western Canada over the period 1882 to 2001. Because "sampling of small-scale events such as destructive windstorms in the prairie provinces of Canada depends strongly on the human influences of time and space changes in rural settlement patterns," Hage writes, "extensive use was made of Statistics Canada data on farm numbers by census years and census areas, and on farm sizes by census years in attempts to correct for sampling errors." The results of these operations are stated quite simply: "All intense storms showed no discernible changes in frequency after 1940.

Changnon (2003) investigated trends in both severe weather events and changes in societal and economic factors over the last half of the twentieth century in the United States. He found trends in various weather extremes were mixed, noting "one trend is upwards (heavy rains-floods), others are downward (hail, hurricanes, tornadoes, and severe thunderstorms), and others are unchanging flat trends (winter storms and wind storms)." Had the analysis of heavy rains and floods been extended back to the beginning of the twentieth century, the longer-term behavior of this phenomenon would have been found to be indicative of no net change over the past hundred years, as demonstrated by Kunkel (2003).

As to why insurance losses rose so rapidly over the past several decades, Changnon reports "the primary reason for the large losses [was] a series of societal shifts (demographic movements, increasing wealth, poor construction practices, population growth, etc.) that collectively had increased society's vulnerability." When properly adjusted for societal and economic trends over the past half-century, monetary loss values associated with damages inflicted by extreme weather events "do not exhibit an upward trend." Changnon emphasizes, "the adjusted loss values for these extremes [do] not indicate a shift due to global warming." These real-world observations, he notes, "do not fit the predictions, based on GCM simulations under a warmer world resulting from increased CO_2 levels, that call for weather extremes and storms to increase in frequency and intensity."

Khandekar (2003) briefly reviews what he learned about extreme weather events in Canada while conducting a study of the subject for the government of Alberta. He notes his research led him to conclude "extreme weather events such as heat waves, rain storms, tornadoes, winter blizzards, etc., [were] not increasing anywhere in Canada at [that] time." In addition, he notes a special issue of *Natural Hazards* (Vol. 29, No. 2) concluded much the same thing about other parts of the world, citing a survey article by Robert Balling, who found "no significant increase in overall severe storm activity (hurricanes, thunderstorms/tornadoes, winter blizzards) across the conterminous United States," and the previously cited work of Changnon.

Daoust (2003) catalogued daily tornado frequencies for each county of Missouri (USA) for the period 1950–2002, after which he transformed the results into monthly time series of tornado days for each of the state's 115 counties, its six climatic divisions, and the entire state. This work revealed the presence of positive trends in tornado-day time series for five of the six climatic divisions of Missouri, but none of these trends was statistically significant. For the sixth climatic division, the trend was significant but negative. At the level of the entire state, Daoust reported "for the last 53 years, no long-term trend in tornado days can be found."

Diffenbaugh *et al*. (2008) briefly reviewed what is known about responses of U.S. tornadoes to rising temperatures. On the theoretical side of the issue, they indicate there are competing ideas with regard to whether tornadoes might become more or less frequent and/or severe as the planet warms. On the observational side, there is also much uncertainty about the matter. They write, for example, "the number of tornadoes reported in the United States per year has been increasing steadily (~14 per year) over the past half century," but they note "determining whether this is a robust trend in tornado occurrence is difficult" because "the historical record is both relatively short and non-uniform in space and time." In addition, the increase in yearly tornado numbers runs parallel with the concurrent increase in the country's population, which makes for better geographical coverage and more complete (i.e., numerous) observations.

On the other hand, the three researchers report the number of tornadoes classified as the most damaging (F2–F5 on the Fujita scale) may have truly decreased over the past five decades (1954–2003), as their frequency of occurrence actually runs counter to the trend of the nation's population. The graphs they present show yearly F2–F5 tornado numbers in the latter half of the record period dropping to only about half of what they were during the first half of the record, while corresponding data from the U.S. Southern Great Plains show damaging tornado numbers dropping to only about a third of what they were initially. Nevertheless, Diffenbaugh *et al*. consider the question posed in the title of their paper—Does global warming influence tornado activity?—to be unresolved, stating "determining the actual background occurrence and trend in tornado activity over recent decades will certainly require further development of other analysis approaches."

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7.7.5 Wind

Differences in pressure, or pressure gradients, cause wind. How, then, does wind respond to rising temperatures? Several studies have addressed different aspects of this question in recent years. McPhaden and Zhang (2002), for example, studied surface winds over the Pacific Ocean and the currents they produce in the water below that flow outward from the equator and eventually sink and flow back from both hemispheres to meet and rise near the equator. They discovered over the period 1950–1999, this overturning circulation of the ocean "has been slowing down since the 1970s, causing a decrease in upwelling of about 25% in an equatorial strip between 9°N and 9°S." The scientists say the gradual decline may have been caused by global warming—the opposite of what climate models suggest should happen—but they also note natural variability may just as easily have been the cause of what they observed.

Siegismund and Schrum (2001) investigated wind speed characteristics over the North Sea for the period 1958–1997. They found "the annual mean wind speed for the North Sea shows a rising trend of ~10% during the last 40 years," in harmony with what climate models typically predict. In addition, they determined "since the early 1970s 'strong wind' events are more frequent than in the 1960s," also in harmony with model-based predictions. As for the cause of these phenomena, however, the researchers say their data "may suggest an anthropogenic origin, but this hypothesis can neither be supported nor disproved by analyzing such short time series."

Slonosky *et al*. (2000) analyzed atmospheric surface pressure data from 51 stations located throughout Europe and the eastern North Atlantic over the period 1774–1995, finding atmospheric circulation over Europe was "considerably more variable, with more extreme values in the late 18th and early 19th centuries than in the 20th century." Pirazzoli (2000) studied tide-gauge and meteorological (wind and atmospheric pressure) data over the period 1951–1997 for the northern portion of the Atlantic coast of France, discovering atmospheric depressions (storms) and strong surge winds for this region "are becoming less frequent."

Barring and von Storch (2004) analyzed pressure readings for Lund (since 1780) and Stockholm (since 1823) in Sweden to create a record of storminess. They found their proxy time series for storminess were "remarkably stationary in their mean, with little variations on time scales of more than one or two decades." Specifically, they report "the 1860s–70s was a period when the storminess indices showed general higher values," as was the 1980s–1990s, but subsequently, "the indices have returned to close to their long-term mean." Barring and von Storch conclude their storminess proxies "show no indication of a long-term robust change towards a more vigorous storm climate." In fact, during "the entire historical period," they write, storminess was "remarkably stable, with no systematic change and little transient variability."

Contemporaneously, Hanna *et al*. (2004) examined several climatic variables, including air pressure, temperature, precipitation, and sunshine data, over the past century in Iceland, to determine whether there is "possible evidence of recent climatic changes" in that cold island nation. For the period 1820–2002, annual and monthly pressure data exhibited semi-decadal oscillations but no significant upward or downward trend. As for what may be responsible for the oscillations in the data, they mention the likely influence of the Sun, noting a 12-year peak in their spectral analysis of the pressure data is "suggestive of solar activity."

Expanding the solar/pressure link further, Veretenenko *et al*. (2005) examined the potential influence of galactic cosmic rays (GCR) on the long-term variation of North Atlantic sea-level pressure over the period 1874–1995. Comparisons of long-term variations in cold-season (October–March) sea-level pressure with different solar/geophysical indices revealed increasing sea-level pressure coincided with a secular rise in solar/geomagnetic activity accompanied by a decrease in GCR intensity, whereas long-term decreases in sea-level pressure were observed during periods of decreasing solar activity and rising GCR flux. Spectral analysis further supported a link between sea-level pressure, solar/geomagnetic activity, and GCR flux, as similar spectral characteristics (periodicities) were present among all datasets at time scales ranging from approximately 10 to 100 years.

The results of this analysis support a link between long-term variations in cyclonic activity and trends in solar activity/GCR flux in the extratropical latitudes of the North Atlantic. As to how this relationship works, Veretenenko *et al*. hypothesize GCR-induced changes in cloudiness alter long-term variations in solar and terrestrial radiation receipt in this region, which in turn alters tropospheric temperature gradients and produces conditions more favorable for cyclone formation and development.

Gulev and Grigorieva (2004) used the Voluntary Observing Ship wave data of Worley *et al*. (2005) to characterize significant wind-driven wave height (HS) over various ocean basins throughout all or parts of the twentieth century. The two Russian scientists report "the annual mean HS visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950," which appears to vindicate the IPCC's thoughts on the subject. "However," they continue, "for the period 1885–2002 there is no secular trend in HS in the Atlantic," and "the upward trend in the Pacific for this period ... becomes considerably weaker than for the period 1950–2002."

Gulev and Grigorieva also note the highest annual HS in the Pacific during the first half of the century "is comparable with that for recent decades," and "in the Atlantic it is even higher than during the last 5 decades." In the Atlantic the mean HS of the entire decade of the 1920s is higher than that of any recent decade; and the mean HS of the last half of the 1940s is also higher than that of the last five years of the record. In the Pacific the mean HS from the late 1930s to the late 1940s may have been higher than that of the last decade of the record, although there is a data gap in the middle of this period that precludes us from conclusively proving this latter point. Given such findings, it is clear annual mean wind-driven wave heights over the last decade of the twentieth century were not higher than those that occurred earlier in the century.

McVicar *et al*. (2010) note there has been great interest "in the widespread declining trends of wind speed measured by terrestrial anemometers at many mid-latitude sites over the last 30–50 years," citing the work of Roderick *et al*. (2007), McVicar *et al*. (2008), Pryor *et al*. (2009), and Jiang *et al*. (2010). They state this *stilling*, as it has come to be called, is "a key factor in reducing atmospheric evaporative demand," which drives actual evapotranspiration when water availability is not limiting, as in the case of lakes and rivers. In addition, they note near-surface wind speed (u) nearly always increases as land-surface elevation (z) increases, as demonstrated by the work of McVicar *et al*. (2007). Increasing wind speeds lead to increases in atmospheric evaporative demand, whereas decreasing wind speeds do the opposite, and both of these changes can be of great significance for people dependent upon water resources derived from mountainous headwater catchments. It would be advantageous to learn how the change in near-surface wind speed with ground elevation may have varied over the last few decades of global warming, since, as the authors note, "over half the global population live in catchments with rivers originating in mountainous regions (Beniston, 2005), with this water supporting about 25% of the global gross domestic product (Barnett *et al*., 2005)."

Defining *u*z as change in wind speed with change in elevation (*u*z = Δu/Δz, where Δu = u2-u1, Δz = z2-z1, and z2 > z1), McVicar *et al*. calculated monthly averages of *u*z based on monthly average *u* data from low-set (10-meter) anemometers maintained by the Chinese Bureau of Meteorology at 82 sites in central China and by MeteoSwiss at 37 sites in Switzerland from January 1960 through December 2006. The authors report their research constituted "the first time that long-term trends in *u*z in mountainous regions have been calculated." The seven scientists found, "for both regions *u*z trend results showed that *u* has declined more rapidly at higher than lower elevations." Such a decline in wind speed at many mid-latitude sites and a further decline in wind speed at higher elevations should act to reduce water loss via evaporation from high-altitude catchments in many of the world's mountainous regions, providing more water for people who obtain it from such sources. McVicar *et al*. note the "reductions in wind speed will serve to reduce rates of actual evapotranspiration partially compensating for increases in actual evapotranspiration due to increasing air temperatures."

More recently, Alexander *et al*. (2011) analyzed storminess across the whole of southeast (SE) Australia using extreme (standardized seasonal 95th and 99th%iles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century. According to the four researchers, their results "show strong evidence for a significant reduction in intense wind events across SE Australia over the past century." More specifically, "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease." "In terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Ekman (1999) utilized a sea-level record beginning in 1774 from Stockholm, Sweden to investigate long-term trends in the levels of the Baltic and North Seas and the relationships of these trends to various climatic factors. They determined there had been throughout the 1800s a rapidly decreasing number of dominating winter winds from the northeast. Since such winds typically tend to reduce sea levels at Stockholm, this regime shift led to a gradual increase in the rate of rise of sea level there. Subsequently, the winter winds gradually shifted to where the dominant airflow was from the southwest. Since winds from this direction tend to promote high sea levels at Stockholm, the rate of rise in sea level there continued to increase. The net result of these wind regime changes was thus a continual increase in the rate of rise of sea level at Stockholm over the entire two-century period, resulting in a mean sea-level rise of 1.0 mm/year over the twentieth century. Thus, as the world transitioned from the Little Ice Age to the Modern Warm Period, sea levels around Stockholm rose, not from the melting of polar ice but from a systematic shifting of wind direction.

In another study from Sweden, cores of peat taken from two raised bogs in the near-coastal part of Halland, Southwest Sweden (Boarps Mosse and Hyltemossen), were examined by Björck and Clemmensen (2004) for their content of wind-transported clastic material, to determine temporal variations in Aeolian Sand Influx (ASI), which is correlated with winter wind climate in that part of the world. The researchers report, "the ASI records of the last 2500 years (both sites) indicate two timescales of winter storminess variation in southern Scandinavia." Specifically, "decadal-scale variation (individual peaks) seems to coincide with short-term variation in sea-ice cover in the North Atlantic and is thus related to variations in the position of the North Atlantic winter season storm tracks," and "centennial-scale changes—peak families, like high peaks 1, 2 and 3 during the Little Ice Age, and low peaks 4 and 5 during the Medieval Warm Period—seem to record longer-scale climatic variation in the frequency and severity of cold and stormy winters."

Björck and Clemmensen also found a striking association between the strongest of these winter storminess peaks and periods of reduced solar activity. They note, for example, the solar minimum between AD 1880 and 1900 "is almost exactly coeval with the period of increased storminess at the end of the nineteenth century, and the Dalton Minimum between AD 1800 and 1820 is almost coeval with the period of peak storminess reported here." In addition, they state an event of increased storminess they dated to AD 1650 "falls at the beginning of the Maunder solar minimum (AD 1645–1715)," and they find a period of high ASI values between AD 1450 and 1550 with "a very distinct peak at AD 1475," noting this period coincides with the Sporer Minimum of AD 1420–1530. They note the latter three peaks in winter storminess all occurred during the Little Ice Age and "are among the most prominent in the complete record."

Clarke *et al*. (2002) used an infrared stimulated luminescence technique to date sands from dunes in the Aquitaine region of southwest France, identifying three main phases of wind-induced dune formation: 4,000–3,000 years ago during the long cold interval that preceded the Roman Warm Period; 1,300–900 years ago during the early to middle Medieval Warm Period, but during what they describe as its cooler periods; and 550–250 years ago during the Little Ice Age, again during what they call its cooler periods. In addition, a search of the literature allowed the scientists to identify similar massive wind-induced movements of sand in England, Scotland, Denmark, Portugal, and the Netherlands during these periods of relative coolness. For the most recent of these cool periods, they also note the existence of voluminous historical records that describe many severe North Atlantic wind storms.

Working with insurance industry data, Changnon (2009) analyzed "catastrophes caused solely by high winds" that had had their losses adjusted so as to make them "comparable to current year [2006] values." Although the average monetary loss of each year's catastrophes "had an upward linear trend over time, statistically significant at the 2% level," when the number of each year's catastrophes was considered, it was found "low values occurred in the early years (1952–1966) and in later years (1977–2006)," and "the peak of incidences came during 1977–1991." Changnon reports "the fit of a linear trend to the annual [catastrophe number] data showed no upward or downward trend."

Two years later in a similar study, Changnon (2011) calculated trends in a number of straight-line wind-related parameters over the period 1950–2006. According to the Illinois State Water Survey researcher, high winds—excluding those associated with hurricanes, tornadoes, snowstorms, blizzards, and heavy rainstorms—are one of the United States' leading types of damage-producing storms. These straight-line windstorms, as they are called, produce annual U.S. property and crop losses totaling $380 million and rank as the nation's sixth-most-damaging type of severe weather.

With respect to whether the global warming of the past half-century has had any significant effect on straight-line windstorm frequency or ferocity, Changnon notes "the distribution of losses over time showed high values in recent years, 1997–2006, and the 55-year distribution had a statistically significant upward trend over time." However, he further describes how a number of adjustments to loss data of the past needed to be made "to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current year values, 2006 in this study." When these adjustments were made, he reports the 55-year time trend "was not up or down." He finds "the national temporal distribution of catastrophic windstorms during 1952–2006 has a flat trend," suggesting, the global warming of the past half-century or so has had no noticeable impact on the net frequency or ferocity of straight-line windstorms in the United States.

The research summarized here suggests the cool nodes of Earth's millennial-scale climatic oscillation are more prone to high wind conditions than are its warm nodes, and the gradual warming of the globe over the past two centuries has probably reduced wind speeds over many portions of the planet, although there may be regional exceptions. In addition, changes in wind speed have implications for a host of other phenomena, from reconstructions of sea-level histories to fluctuations in evaporation and wave heights. Finally, there is some evidence these wind-driven phenomena may be solar-induced.

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7.8 Hurricanes

For many years, nearly all climate model output suggested tropical cyclones (TC) should become both more frequent and more intense as planetary temperatures rise. As a result of such projections, scientists worked to improve the temporal histories of these particular TC characteristics for various ocean basins around the world in an effort to evaluate the plausibility of such projections. In nearly all instances, the research revealed TCs have not been increasing in frequency or magnitude during the era of modern instrumentation and rise of atmospheric CO_2.

As a result of these findings, the IPCC revised its conclusion on hurricanes, stating in its most recent report, "recent re-assessments of tropical cyclone data do not support the [Fourth Assessment Report] conclusions of an increase in the most intense tropical cyclones or an upward trend in the potential destructiveness of all storms since the 1970s. There is low confidence that any reported long-term changes are robust, after accounting for past changes in observing capabilities."

Not willing to disavow the model projection fully, the IPCC adds, "over the satellite era, increases in the intensity of the strongest storms in the Atlantic appear robust" (p. 62 of the Technical Summary, Second Order Draft of AR5, dated October 5, 2012). In addition, despite the vast array of observational data that do not support the model projections, the IPCC continues to project future increases in certain TC parameters for the globe (increase in TC intensity) and for individual ocean basins (increase in the number of intense storms):

> Projections for the 21st century indicate that it is likely that the global frequency of tropical

> cyclones will either decrease or remain essentially unchanged, concurrent with a likely global increase in both tropical cyclone maximum wind speed and rainfall rates, but there is lower confidence in region-specific projections. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 59).

> … it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates … It is more likely than not that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming. (Technical Summary, Second Order Draft of AR5, dated October 5, 2012, p. 62).

In light of the IPCCs continued claims regarding hurricanes, Section 7.10 reviews the scientific literature to present a detailed examination of what has been learned with respect to such storms in various ocean basins across the globe. The results of that examination reveal real-world data do not support, and in fact essentially invalidate, the model claims. Global warming, whether CO_2-induced or natural, is likely to have no measurable influence on the frequency or intensity of tropical cyclones.

7.8.1 Atlantic Ocean

Data presented in numerous peer-reviewed scientific studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Atlantic Ocean.

7.8.1.1 Frequency

7.8.1.1.1 The Past Century

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what the IPCC describes as unprecedented global warming?

In an early attempt to answer this question, Bove *et al*. (1998) examined the characteristics of all recorded landfalling U.S. Gulf Coast hurricanes—defined as those whose eyes made landfall between Cape Sable, Florida and Brownsville, Texas—from 1896 to 1995. They found the first half of this period saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade, and the same was true for intense hurricanes of category 3 or more on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes both trended downward from 1966 to the end of the period investigated, with the decade 1986–1995 exhibiting the fewest intense hurricanes of the century. The three researchers conclude, "fears of increased hurricane activity in the Gulf of Mexico are premature."

Noting the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but during the preceding four years (1991–1994) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al*. (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. They found "perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region." They also note, "in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea level pressure, abnormally warm ocean waters, and very humid values of total precipitable water."

The enhanced activity of the 1995 Atlantic hurricane season also may have been affected by the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Most important, perhaps, was what Landsea *et al*. called the "dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions," which contributed to what they described as "the dramatic reversal" of weather characteristics "which dominated during the [prior] four hurricane seasons."

The four researchers note, "Some have asked whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic 'greenhouse' gases." They concluded "such an interpretation is not warranted," because the factors noted above seem sufficient to explain the observations. "Additionally," they write, "Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean intensity of all named storms over the past few decades," and "this holds true even with the inclusion of 1995's Atlantic hurricane season."

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al.* (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944–1996, decreasing trends were found for the total number of hurricanes, the number of intense hurricanes, the annual number of hurricane days, the maximum attained wind speed of all hurricane storms averaged over the course of a year, and the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they report the total number of Atlantic hurricanes making landfall in the United States decreased over the 1899–1996 time period, and normalized trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of $728 million per decade.

Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States during the period 1935–1998. They found "a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of -0.011 ± 0.0086 storms per year." They expressly note "the estimated trend slope is negative," meaning the yearly number of such storms is decreasing, just the opposite of what they described as the "frequent hypothesis ... that global warming is causing increased storm activity." Their statistical analysis indicates "the trend slope is not significantly different from zero."

Easterling *et al.* (2000) point out the mean temperature of the globe rose by about 0.6°C over the past century. They looked for possible impacts of this phenomenon on extreme weather events, which if found to be increasing, "would add to the body of evidence that there is a discernible human affect on the climate." Their search revealed few changes of significance, although they did determine "the number of intense and landfalling Atlantic hurricanes has declined."

Balling and Cerveny (2003) wrote, "many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones," but they note empirical studies had failed to reveal any such relationships. They also note "some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events," and these relationships have not been thoroughly studied with historical real-world data.

The two Arizona State University climatologists constructed a daily database of tropical storms that occurred in the Caribbean Sea, Gulf of Mexico, and western North Atlantic Ocean over the period 1950–2002, generating "a variety of parameters dealing with duration, timing, and location of storm season," after which they tested for trends in these characteristics, attempting to explain the observed variances in the variables using regional, hemispheric, and global temperatures. They "found no trends related to timing and duration of the hurricane season and geographic position of storms in the Caribbean Sea, Gulf of Mexico and tropical sector of the western North Atlantic Ocean." They also "could find no significant trends in these variables and generally no association with them and the local ocean, hemispheric, and global temperatures."

Elsner *et al.* (2004) conducted a changepoint analysis of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the twentieth century. This technique, they write, "quantitatively identifies temporal shifts in the mean value of the observations." Their work revealed "major North Atlantic hurricanes have become more frequent since 1995," but at "a level reminiscent of the 1940s and 1950s." That appears to be an overstatement of their findings; their data indicate the mean annual hurricane count for the seven-year period 1995–2001 was 3.86, while the mean count for the 14-year period 1948–1961 was 4.14. They also report, "in general, twentieth-century U.S. hurricane activity shows no abrupt shifts," noting there was an exception over Florida, "where activity decreased during the early 1950s and again during the late 1960s." They also found "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

Elsner *et al.*'s work contradicts the claim that global warming leads to more intense hurricane activity. North Atlantic hurricane activity did not increase over the twentieth century, during which the IPCC says Earth experienced a temperature increase unprecedented over the past two millennia. Moreover, hurricane activity also did not increase, and in fact decreased, in response to the more sporadic warming associated with periodic El Niño conditions.

Virmani and Weisberg (2006) report "the 2005 hurricane season saw an unprecedented number of named tropical storms since records began in 1851." Moreover, they note it followed "on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path." They wondered whether the increased hurricane activity occurred in response to recent global warming or if it bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

The two researchers determined "latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea level pressure," which "resulted in anomalously high sea surface temperatures" that "contributed to earlier and more intense hurricanes in 2005." They note "these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998." In addition, they found no "clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation." It would appear the 2005 hurricane season was not as unusual as many people have made it out to be, and there is no compelling reason to ascribe whatever degree of uniqueness it may have possessed to recent global warming.

Mann and Emanuel (2006) used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871–2005, and Holland and Webster (2007) analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both papers linked these changes to anthropogenic greenhouse warming.

In a compelling rebuttal of these conclusions, Landsea (2007) cited a number of possible biases in the cyclone frequency trends derived in the two studies, concluding "improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones."

Parisi and Lund (2008) calculated return periods of Atlantic-basin U.S. landfalling hurricanes based on "historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques" for each of the categories (1–5) of the Saffir-Simpson Hurricane Scale. Return periods, in ascending Saffir-Simpson Scale category order, were 0.9 years for category 1, 1.3 years for category 2, 2.0 years for category 3, 4.7 years for category 4, and 23.1 years for category 5 hurricanes. In addition, the two researchers reported corresponding non-encounter probabilities in any one hurricane season were calculated to be (category 1) 0.17, (category 2) 0.37, (category 3) 0.55, (category 4) 0.78, and (category 5) 0.95. The hypothesis that U.S. hurricane strike frequencies are "increasing in time"—which is often stated as fact—is "statistically rejected," they conclude.

Chylek and Lesins (2008) applied "simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity and other features of interest." Using a hurricane activity index that integrates hurricane numbers, durations, and strengths, the two researchers report discovering "a quasi-periodic behavior with a period around 60 years superimposed upon a linearly increasing background." However, they note "the linearly increasing background is significantly reduced or removed when various corrections were applied for hurricane undercounting in the early portion of the record." Further noting "the last minimum in hurricane activity occurred around 1980," Chylek and Lesins compared the two 28-year-long periods on either side of this date, finding "a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification." They conclude, "if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured by the 60-year quasi-periodic cycle."

Klotzbach and Gray (2008) employed sea surface temperature (SST) data for the far North Atlantic (50–60°N, 50–10°W) and sea-level pressure (SLP) data for the North Atlantic (0-50°N, 70-10°W) to construct an index of the Atlantic Multidecadal Oscillation (AMO), which they defined as the difference between the standardized SST and SLP anomalies (SST-SLP) for the hurricane season of June–November, and which they evaluated for the period 1878–2006. They compared their results, to which they applied a 1-2-3-

2-1 filter, with a number of hurricane properties.

Klotzbach and Gray's analysis revealed the existence of three positive and two negative AMO phases over the period of their study, as illustrated in Figure 7.8.1.1.1.

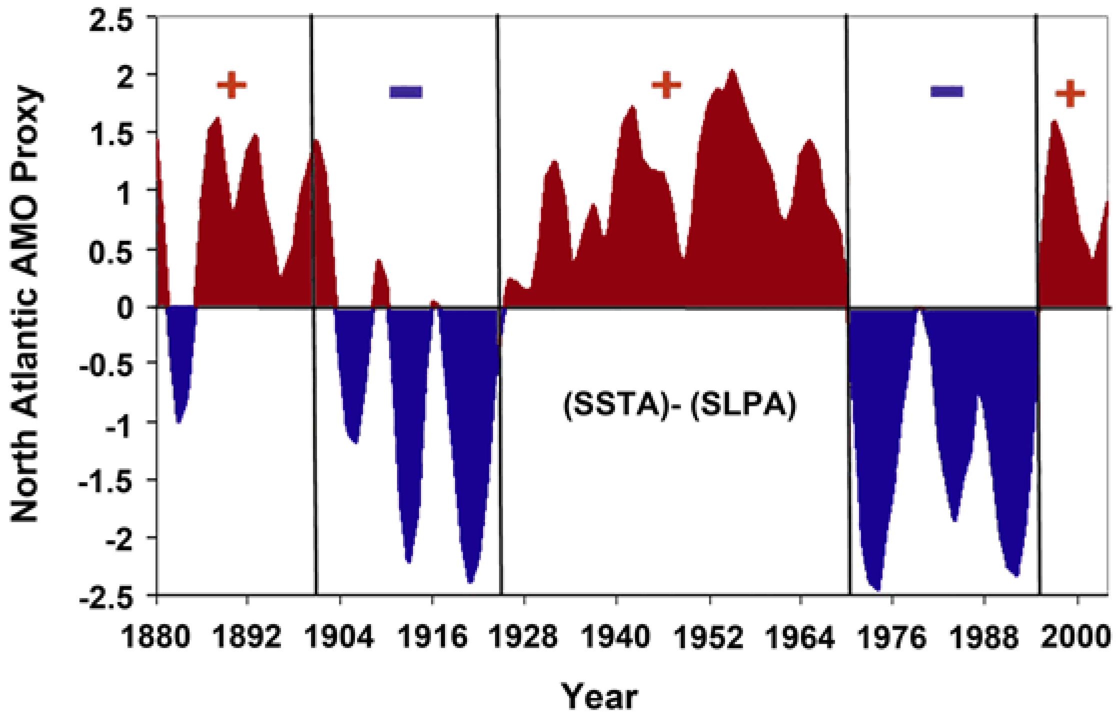

Figure 7.8.1.1.1. North Atlantic AMO Index. Adapted from Klotzbach, P.J. and Gray, W.M. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate* **21**: 3929-3935.

In comparing annually averaged results for tropical cyclone characteristics between the positive and negative AMO phases indicated in the figure, it can be calculated from the tropical cyclone data of the authors that the positive-AMO-phase to negative-AMO-phase ratios of hurricane numbers, hurricane days, major hurricane numbers, and major hurricane days were 1.53, 1.89, 2.00, and 2.46, respectively, over the period studied. For the 20 most positive and 20 most negative AMO years, those ratios, in the same order, were 1.73, 2.41, 2.80, and 4.94. Such calculations demonstrate the North Atlantic AMO is tremendously important to hurricane genesis and development, and this striking natural variability makes it extremely difficult to determine whether there is any long-term trend in the tropical cyclone data that might be attributable to twentieth century global warming.

Zeng *et al*. (2009) "synthesized field measurements, satellite image analyses, and empirical models to evaluate forest and carbon cycle impacts for historical tropical cyclones from 1851 to 2000 over the continental U.S." They found greater forest impacts and biomass loss between 1851 and 1900 from hurricane activity than during the twentieth century. On average, the authors found "147 million trees were affected each year between 1851 and 1900," which led to "a 79-Tg annual biomass loss." Average annual forest impact and biomass loss between 1900 and 2000 "were 72 million trees and 39 Tg, which were only half of the impacts before 1900." The authors say these results are in "accordance with historical records showing that Atlantic tropical cyclones were more active during the period from 1870 to 1900." They also note the amount of carbon released from the downed and damaged trees "reached a maximum value in 1896, after which it continuously decreased until 1978," when it leveled off for the remaining two decades of the twentieth century.

Hagen and Landsea (2012) point out "previous studies state that there has been an increase in the number of intense hurricanes and [they] attribute this increase to anthropogenic global warming," but "other studies claim that the apparent increased hurricane activity is an artifact of better observational capabilities and improved technology for detecting these intense hurricanes." They focused their research on the ten most recent Category 5 hurricanes known to have occurred in the Atlantic Ocean, from Hurricane Andrew in 1992 to Hurricane Felix of 2007. Placing these ten hurricanes into the context of the technology available from 1944 to 1953—the first decade of aircraft reconnaissance—they determined how many of these Category 5 hurricanes likely would have been recorded as Category 5 if they had occurred during the earlier period, using only the observations likely to have been available with then-existing technology and observational networks.

The two U.S. researchers report "there are likely to have been several Category 4 and 5 hurricanes misclassified as being weaker prior to the satellite era." For example, "if the ten most recent Category 5 hurricanes occurred during the late-1940s period, only two of them would be considered Category 5 hurricanes (and three of ten for the early-1950s period)." In addition, "three recent Category 4 hurricanes were identified that would likely not have been counted as major hurricanes if they had occurred during the late 1940s/1950s." Hagen and Landsea conclude, "counts of Category 4 and 5 hurricanes (at least through 1953 and likely beyond that year) are not nearly as reliable as they are today." They further conclude "future studies that discuss frequency trends of Atlantic basin Category 4 and 5 hurricanes must take into account the undercount biases that existed prior to the geostationary satellite era due to the inability to observe these extreme conditions."

Villarini *et al*. (2011) used the statistical model developed by Villarini *et al*. (2010), in which "the frequency of North Atlantic tropical storms is modeled by a conditional Poisson distribution with a rate of occurrence parameter that is a function of tropical Atlantic and mean tropical sea surface temperatures (SSTs)," to examine "the impact of different climate models and climate change scenarios on North Atlantic and U.S. landfalling tropical storm activity," and reconcile "differing model projections of changes in the frequency of North Atlantic tropical storms in a warmer climate."

The five researchers report their results "do not support the notion of large increases in tropical storm frequency in the North Atlantic basin over the twenty-first century in response to increasing greenhouse gases." They also note "the disagreement among published results concerning increasing or decreasing North Atlantic tropical storm trends in a warmer climate can be largely explained (close to half of the variance) in terms of the different SST projections (Atlantic minus tropical mean) of the different climate model projections."

They also find, "for the SRES A1B scenario and 24 climate models, over the twenty-first century there is a large spread among projected trends in tropical storm activity in the North Atlantic basin, with a mean of -0.83 tropical storm per century and a standard deviation of 2.48 tropical storms per century." And with respect to U.S. land-falling tropical storms, they state, "results based on 7 climate models point to a statistically significant increasing trend, while 6 point to a decreasing trend," suggesting the models are inconsistent in projecting what will happen over the current century. Villarini *et al*. (2011) conclude, among other things, "there is a considerable level of uncertainty in climate change projections that will remain effectively 'irreducible,' as no current prospects exist for skillful century-scale predictions of unforced climate variability."

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7.8.1.1.2 The Past Few Centuries

Has the warming of the past century, which rescued the world from the extreme cold of the Little Ice Age, led to the formation of more numerous Atlantic Basin tropical storms and hurricanes? Several studies have broached this question with sufficiently long data records to provide reliable answers.

Elsner *et al*. (2000) provided a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales, and they presented data on major hurricane occurrences in 50-year intervals for Bermuda, Jamaica, and Puerto Rico. These data reveal hurricanes occurred at far lower frequencies in the last half of the twentieth century than they did in the preceding five 50-year periods at all three of the locations studied. From 1701 to 1850, for example, when Earth was in the grip of the Little Ice Age, major hurricane frequency was 2.77 times greater at Bermuda, Jamaica, and Puerto Rico than it was from 1951 to 1998. From 1851 to 1950, when the planet was in transition from the Little Ice Age to current conditions, the three locations experienced a mean hurricane frequency 2.15 times greater than what they experienced from 1951 to 1998.

Such findings for the Caribbean Sea were echoed by Elsner (2008) in his summary of the *International Summit on Hurricanes and Climate Change* held in May 2007. He states paleotempestology—which he defines as the study of prehistoric storms based on geological and biological evidence—indicates the presence of more hurricanes in the northeastern Caribbean Sea "during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today." He goes on to say his work provides evidence that "today's warmth is not needed for increased storminess."

In another multicentury study, Boose *et al*. (2001) used historical records to reconstruct hurricane damage regimes for the six New England states plus adjoining New York City and Long Island for the period 1620–1997. They find "no clear century-scale trend in the number of major hurricanes." At lower damage levels, fewer hurricanes were recorded in the seventeenth and eighteenth centuries than in the nineteenth and twentieth centuries, but the three researchers conclude "this difference is probably the result of improvements in meteorological observations and records since the early 19th century." With the better records of the past 200 years, it is clear the cooler nineteenth century had five of the highest-damage storms, whereas the warmer twentieth century had only one such storm.

Nyberg *et al*. (2007) developed a history of major (Category 3–5) Atlantic hurricanes over the past 270 years based on proxy records of vertical wind shear and sea surface temperature derived from corals and a marine sediment core. Wind shear and SST are the primary controlling forces for the formation of major hurricanes in the region west of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10°N and 20°N, where 85% of all major hurricanes and 60% of all non-major hurricanes and tropical storms of the Atlantic are formed.

The researchers discovered the average frequency of major Atlantic hurricanes "decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s." They note "a gradual downward trend is evident from an average of ~4.1 (1775–1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s," and "the current active phase (1995–2005) is unexceptional compared to the other high-activity periods of ~1756–1774, 1780–1785, 1801–1812, 1840–1850, 1873–1890 and 1928–1933." They conclude the recent ratcheting up of Atlantic major hurricane activity appears to be simply "a recovery to normal hurricane activity." In a commentary on Nyberg *et al.*'s paper, Elsner (2007) stated "the assumption that hurricanes are simply passive responders to climate change should be challenged," which Nyberg *et al*. do convincingly.

Also noting "global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean," with the implication that "a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State," Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005.

The work revealed "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and of these storms, "14 were hurricanes, 27 were tropical storms, 7 were tropical depressions and 28 were extratropical storms." For Long Island, he reports "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." He finds storm activity was greatest in both the late nineteenth century and the late twentieth century, and "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century." Vermette concludes, "rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century."

Mock (2008) developed a "unique documentary reconstruction of tropical cyclones for Louisiana, USA, that extends continuously back to 1799 for tropical cyclones and to 1779 for hurricanes." Mock says this record, derived from daily newspaper accounts, private diaries, plantation diaries, journals, letters, and ship records and augmented "with the North Atlantic hurricane database as it pertains to all Louisiana tropical cyclones up through 2007," is "the longest continuous tropical cyclone reconstruction conducted to date for the United States Gulf Coast." The record reveals "the 1820s/early 1830s and the early 1860s are the most active periods for the entire record."

The University of South Carolina researcher says "the modern records which cover just a little over a hundred years [are] too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude." He states, "if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [those storms] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005."

Chenoweth and Divine (2008) examined newspaper accounts, ships' logbooks, meteorological journals, and other documents to reconstruct a history of tropical cyclones passing through the 61.5°W meridian between the coast of South America (~9.7°N) and 25.0°N over the period 1690–2007, which they describe as "the longest and most complete record for any area of the world." The two authors found "no evidence of statistically significant trend in the number of tropical cyclones passing through the region on any time scale." They also note "hurricane frequency is down about 20% in the 20th century compared to earlier centuries," and "this decline is consistent with the 20th century observed record of decreasing hurricane landfall rates in the U.S. (Landsea *et al*., 1999; Elsner *et al*., 2004) and proxy reconstruction of higher tropical cyclone frequency in Puerto Rico before the 20th century (Nyberg *et al*., 2007), as well as model-simulated small changes in Atlantic basin tropical cyclone numbers in a doubled CO_2 environment (Emanuel *et al*., 2008; Knutson *et al*., 2008)." In addition, they report "the period 1968–1977 was probably the most inactive period since the islands were settled in the 1620s and 1630s," which, in their words, "supports the results of Nyberg *et al*. (2007) of unprecedented low frequency of major hurricanes in the 1970s and 1980s."

Following up on their work four years later, Chenoweth and Divine (2012) examined the records employed in their earlier paper in more detail, determining "the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian." Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends.

Chenoweth and Divine report their record of tropical cyclone activity "reveals no trends in LACE in the best-sampled regions for the past 320 years," and "even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or LACE," noting these results are similar to those reported earlier by them (Chenoweth and Divine, 2008) on tropical cyclone counts. In addition, they indicate LACE along the 61.5°W meridian is "highly correlated" with Atlantic-Basin-wide ACE.

Wang and Lee (2008) used the "improved extended reconstructed" sea surface temperature (SST) data described by Smith and Reynolds (2004) for the period 1854–2006 to examine historical temperature changes over the global ocean, after which they regressed vertical wind shear—"calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data"—onto a temporal variation of global warming defined by the SST data. They discovered warming of the surface of the global ocean is typically associated with a secular increase of tropospheric vertical wind shear in the main development region (MDR) for Atlantic hurricanes, and the long-term increased wind shear of that region has coincided with a weak but robust downward trend in U.S. landfalling hurricanes. However, this relationship has a pattern to it, whereby local ocean warming in the Atlantic MDR reduces the vertical wind shear there, whereas "warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes."

The two researchers conclude "the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes" to date, "warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes." As for the future, they write, "whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans."

Vecchi and Knutson (2008) point out "there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency." They derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) missed by the observing system in the pre-satellite era (1878–1965), after which they analyzed trends of reconstructed TC numbers and duration over various time periods and assessed whether those trends might have been related to trends in sea surface temperature over the main development region of North Atlantic TCs.

Vecchi and Knutson found "the estimated trend for 1900–2006 is highly significant (+~4.2 storms century^{-1})" but "strongly influenced by a minimum in 1910–30, perhaps artificially enhancing significance." When using their base case adjustment for missed TCs and considering the entire 1878–2006 record, they find the trend in the number of TCs is only "weakly positive" and "not statistically significant," and they note the trend in average TC duration over the 1878–2006 period "is negative and highly significant."

Similar shortcomings in the observational record have been reported by other researchers. Landsea *et al*. (2010) note "records of Atlantic basin tropical cyclones (TCs) since the late nineteenth century indicate a very large upward trend in storm frequency," and they state this increase in documented TCs "has been previously interpreted as resulting from anthropogenic climate change." The note "improvements in observing and recording practices provide an alternative interpretation for these changes" and report "recent studies suggest that the number of potentially missed TCs is sufficient to explain a large part of the recorded increase in TC counts."

Landsea *et al*. explored the influence of another factor—TC duration—on observed changes in TC frequency, working with the widely used Atlantic hurricane database known as HURDAT. They found the occurrence of short-lived storms of two days duration or less had increased dramatically, from less than one per year in the late nineteenth and early twentieth centuries to about five per year since about AD 2000, whereas numbers of medium- to long-lived storms had increased "little, if at all." They conclude the previously documented increase in total TC frequency since the late nineteenth century in the database was "primarily due to an increase in very short-lived TCs."

Landsea *et al*. next conducted a sampling study based on the distribution of ship observations, which provided quantitative estimates of the frequency of missed TCs with durations exceeding two days. Upon adding the estimated numbers of missed TCs to the time series of moderate and long-lived Atlantic TCs, they found "neither time series exhibits a significant trend since the late nineteenth century."

Landsea *et al*. conclude sub-sampling of TCs back in time will artificially introduce increases in a wide array of TC characteristics, including "frequency of hurricanes and major hurricanes, duration of TCs, length of season, peak intensity, and integrated TC measures [like Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI)]," which they say "should not be used directly from HURDAT for climate variability and change studies without consideration of, or quantitatively accounting for, how observational network alterations are affecting these statistics."

Vecchi and Knutson (2011) conducted a new analysis of the characteristics of Atlantic hurricanes whose peak winds exceeded 33 m/s for the period 1878–2008, based on the HURDAT database, developing a new estimate of the number of hurricanes that occurred in the pre-satellite era (1878–1965) based on analyses of TC storm tracks and the geographical distribution of the tracks of the ships that reported TC encounters. The two researchers report "both the adjusted and unadjusted basin-wide hurricane data indicate the existence of strong interannual and decadal swings." Although "existing records of Atlantic hurricanes show a substantial increase since the late 1800s," their analysis suggests "this increase could have been due to increased observational capability." They write, "after adjusting for an estimated number of 'missed' hurricanes (including hurricanes that likely would have been miss-classified as tropical storms), the secular change since the late-nineteenth century in Atlantic hurricane frequency is nominally negative—though not statistically significant." The two researchers from NOAA's Geophysical Fluid Dynamics Laboratory say their results "do not support the hypothesis that the warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase."

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7.8.1.1.3 The Past Few Millennia

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? Several studies have examined thousand-year reconstructions of the region's intense hurricane activity.

Liu and Fearn (1993) analyzed sediment cores retrieved from the center of Lake Shelby in Alabama (USA) to determine the history of intense (Category 4 and 5) hurricane activity over the past 3,500 years. Over the period of their study, "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years." The researchers report the last of these hurricane strikes occurred about 700 years ago. It would therefore appear twentieth century global warming has not accelerated the occurrence of such severe storm activity.

Seven years later, Liu and Fern (2000) studied 16 sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico over the past 7,000 years. Twelve major hurricanes of Category 4 or 5 intensity were found to have struck the Western Lake region during this period. Eleven of the 12 events occurred during a 2,400-year period between 1,000 and 3,400 years ago. Only one major hurricane strike was recorded between 0 and 1,000 years ago, and no major hurricane strikes were recorded between 3,400 and 7,000 years ago.

The two researchers say a probable explanation for the "remarkable increase in hurricane frequency and intensity" that affected the Florida Panhandle and Gulf Coast after 1,400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift south and the Bermuda High southwest of their earlier Holocene positions, such as would be expected with global cooling. They note, "paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime."

Donnelly and Woodruff (2007) state "it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones," citing the studies of Emanuel (2005) and Webster *et al*. (2005). Al Gore expressed a similar view in his 21 March 2007 testimony to the U.S. Senate's Environment & Public Works Committee. Cognizant of the need to consider a longer record of the frequency of occurrence of intense hurricanes than that used by Emanuel and Webster *et al*., Donnelly and Woodruff developed "a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls."

The two researchers from the Woods Hole Oceanographic Institution detected three major intervals of intense hurricane strikes: one between 5,400 and 3,600 calendar years before present (yr BP, where "present" is AD 1950), one between 2,500 and 1,000 yr BP, and one after 250 yr BP. They also report coral-based sea surface temperature (SST) data from Puerto Rico "indicate that mean annual Little Ice Age (250–135 yr BP or AD 1700–1815) SSTs were 2–3°C cooler than they are now," and they state "an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766–1780 was one of the most active intervals in the period between 1500 and 1800 (Garcia-Herrera *et al*., 2005), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation (Gray *et al*., 2004)."

Donnelly and Woodruff conclude "the

information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia." The two researchers write, "studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al*., 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development."

Wallace *et al*. (2010) collected a total of 37 sediment cores along eight transects within Laguna Madre, an elongated water body located behind the narrow low-elevation barrier that is Texas, USA's South Padre Island, constructing a detailed history of intense hurricane strikes from 5,300 to 900 years before present (BP). They report "there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval," i.e., 5.300–900 yr BP, "implying no direct link between changing climate conditions and annual hurricane impact probability." In addition, they say "there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time."

In discussing their findings, as well as the similar results obtained by others for Western Lake, Florida, and Lake Shelby, Alabama, the two Rice University (Houston, Texas, USA) researchers say current rates of intense hurricane impacts "do not seem unprecedented when compared to intense strikes over the past 5000 years," and "similar probabilities in high-intensity hurricane strikes for the eastern and western Gulf of Mexico do not show any clear-cut out-of-phase relationship that would enlighten us as to climate controls on storm pathways."

Similarly noting "the brief observational record is inadequate for characterizing natural variability in hurricane activity occurring on longer than multi-decadal timescales," Lane *et al*. (2011) sought a means of characterizing hurricane activity prior to the period of modern measurement and historical record-keeping, because "the manner in which tropical cyclone activity and climate interact has critical implications for society and is not well understood." They developed a 4,500-year record of intense hurricane-induced storm surges based on data obtained from "a nearly circular, 200-m-diameter cover-collapse sinkhole (Mullet Pond: 29°55.520'N, 84°20.275'W) that is located on Bald Point near Apalachee Bay, Florida, USA," where "recent deposition of sand layers in the upper sediments of the pond was found to be contemporaneous with significant, historic storm surges at the site modeled using SLOSH and the Best Track, post-1851 AD dataset"; "paleohurricane deposits were identified by sand content and dated using radiocarbon-based age models"; and "marine-indicative foraminifera, some originating at least 5 km offshore, were present in several modern and ancient storm deposits."

The four researchers' reconstructed record of intense hurricanes revealed the frequency of these "high-magnitude" events "peaked near 6 storms per century between 2800 and 2300 years ago." The record suggests intense hurricanes were "relatively rare" with "about 0–3 storms per century occurring between 1900 and 1600 years ago," after which these super-storms exhibited a marked decline, which "began around 600 years ago" and has persisted through the present with "below average frequency over the last 150 years when compared to the preceding five millennia."

Over the past century and a half of increasing fossil fuel utilization and atmospheric CO_2 buildup, the frequency of the most intense category of hurricanes in the Northeastern Gulf of Mexico has been lower than it was over the prior five millennia, which speaks volumes about the claim that continued anthropogenic CO_2 emissions will lead to more frequent super cyclones and hurricanes.

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7.8.1.2 Intensity

Setting the stage for a discussion of the effects of CO_2-induced global warming on Atlantic Ocean hurricane intensity, Free *et al*. (2004) note "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998)," but "because the predicted increase in intensity for doubled CO_2 is only 5%–20%, changes over the past 50 years would likely be less than 2%—too small to be detected easily." In addition, they say "studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al*., 1996; Henderson-Sellers *et al*., 1998; Solow and Moore, 2002)." Several studies have found yearly hurricane numbers to decline as temperatures rise (see Section 7.10.1.1).

Free *et al*. look not for increases in hurricane intensity, but for increases in potential hurricane intensity, because, as they describe it, "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity." They analyzed radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans and compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. Their results "show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." In addition, between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

In the following year, some important new studies prompted a reissuing of the claim that warming enhances tropical cyclone intensity (Emanuel, 2005; Webster *et al*., 2005), but a new review of the subject once again cast doubt on this contention. Pielke *et al*. (2005) begin their discussion by noting "globally there has been no increase in tropical cyclone frequency over at least the past several decades," citing the studies of Lander and Guard (1998), Elsner and Kocher (2000), and Webster *et al*. (2005). Furthermore, they note research on possible future changes in hurricane frequency due to global warming has produced studies that "give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to base any projections about the future."

With respect to hurricane intensity, Pielke *et al*. note Emanuel (2005) claimed to have found "a very substantial upward trend in power dissipation (i.e., the sum over the life-time of the storm of the maximum wind speed cubed) in the North Atlantic and western North Pacific," but "other studies that have addressed tropical cyclone intensity variations (Landsea *et al*., 1999; Chan and Liu, 2004) show no significant secular trends during the decades of reliable records." In addition, Pielke *et al.* point out early theoretical work by Emanuel (1987) "suggested an increase of about 10% in wind speed for a 2°C increase in tropical sea surface temperature," but more recent work by Knutson and Tuleya (2004) points to only a 5% increase in hurricane windspeeds by 2080, and Michaels *et al*. (2005) conclude even this projection is likely twice as great as it should be.

Perhaps of greatest significance to the prediction of future hurricanes and the destruction they may cause is the nature and degree of human occupation of exposed coastal areas. By 2050, for example, Pielke *et al*. report "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between $22 and $60 of increase in damage due to population growth and wealth," citing the findings of Pielke *et al*. (2000). They state, without equivocation, "the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms."

Pielke *et al*. note many continue to claim a significant hurricane–global warming connection for the purpose of advocating anthropogenic CO_2 emissions reductions that "simply will not be effective with respect to addressing future hurricane impacts," additionally noting "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

In a subsequent analysis of Emanuel's (2005) and Webster *et al*.'s (2005) claims that "rising sea surface temperatures (SSTs) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas concentrations," Michaels *et al*. (2006) used weekly averaged 1° latitude by 1° longitude SST data together with hurricane track data of the National Hurricane Center, which provide hurricane-center locations (latitude and longitude in tenths of a degree) and maximum one-minute surface wind speeds (both at six-hour intervals) for all tropical storms and hurricanes in the Atlantic basin that occurred between 1982 (when the SST data set begins) through 2005. Plotting maximum cyclone wind speed against the maximum SST that occurred prior to (or concurrent with) the maximum wind speed of each of the 270 Atlantic tropical cyclones of their study period, they found for each 1°C increase in SST between 21.5°C and 28.25°C, the maximum wind speed attained by Atlantic basin cyclones rises, in the mean, by 2.8 m/s, and thereafter, as SSTs rise still further, the first Category-3-or-greater storms begin to appear. However, they report, "there is no significant relationship between SST and maximum winds at SST exceeding 28.25°C."

Michaels *et al*. conclude, "while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones." The comparison of SSTs actually encountered by individual storms performed by Michaels *et al*.—as opposed to the comparisons of Emanuel (2005) and Webster *et al*. (2005), which utilized basin-wide averaged monthly or seasonal SSTs—refutes the idea that anthropogenic activity has detectably influenced the severity of Atlantic basin hurricanes over the past quarter-century.

Balling and Cerveny (2006) examined temporal patterns in the frequency of intense tropical cyclones (TCs), the rates of rapid intensification of TCs, and the average rate of intensification of hurricanes in the North Atlantic Basin, including the tropical and subtropical North Atlantic, Caribbean Sea, and Gulf of Mexico, where they say there was "a highly statistically significant warming of 0.12°C decade^{-1} over the period 1970–2003 ... based on linear regression analysis and confirmed by a variety of other popular trend identification techniques." They found "no increase in a variety of TC intensification indices," and "TC intensification and/or hurricane intensification rates ... are not explained by current month or antecedent sea surface temperatures (despite observed surface warming over the study period)." Thus they conclude, "while some researchers have hypothesized that increases in long-term sea surface temperature may lead to marked increases in TC storm intensity, our findings demonstrate that various indicators of TC intensification show no significant trend over the recent three decades."

Klotzbach and Gray (2006) note still other papers question the validity of the findings of Emanuel (2005) and Webster *et al*. (2005) "due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea, 2005)." "While major hurricane activity in the Atlantic has shown a large increase since 1995," they note, "global tropical-cyclone activity, as measured by the accumulated cyclone energy index, has decreased slightly during the past 16 years (Klotzbach, 2006)." They "attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal mode and strength of the Atlantic Ocean thermohaline circulation." They note, "historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25–30 years (typical period ~50–60 years; Gray *et al*., 1997; Latif *et al*., 2004)," and "since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15–20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity," demonstrating the science of this subject is far from settled.

Vecchi and Soden (2007a) explored twenty-first century projected changes in vertical wind shear (VS) over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions scenario A1B (atmospheric CO_2 stabilization at 720 ppm by 2100) of the Intergovernmental Panel on Climate Change's *Fourth Assessment Report*, where VS is defined as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa, and where changes are computed between the two 20-year periods 2001–2020 and 2081–2100. The 18-model mean result indicated a prominent increase in VS over the topical Atlantic and East Pacific (10°N–25°N). Noting "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," the two researchers state the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century." They further note, "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America." Consequently, and in addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes (Donnelly and Woodruff, 2007; Nyberg *et al*., 2007), there is now considerable up-to-date model-based evidence for that conclusion.

In a second, closely related paper, Vecchi and Soden (2007b) used climate models and observational reconstructions "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They found "changes in local sea surface temperature are inadequate for characterizing even the sign of changes in potential intensity." Instead, they report "long-term changes in potential intensity are closely related to the regional structure of warming," such that "regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa."

Using this relationship to reconstruct changes in potential intensity over the twentieth century, based on observational reconstructions of sea surface temperature, they found "even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably peaked in the 1930s and 1950s," noting "recent values are near the historical average." The two scientists concluded the response of tropical cyclone activity to natural climate variations "may be larger than the response to the more uniform patterns of greenhouse-gas-induced warming."

Latif *et al*. (2007) analyzed the 1851–2005 history of Accumulated Cyclone Energy or ACE Index for the Atlantic basin. This parameter "takes into account the number, strength and duration of all tropical storms in a season." They then "analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870–2003."

With respect to the first part of their study, they report "the ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but no sustained long-term trend." With respect to the second part of their study, they report "a clear warming trend is seen in the tropical North Atlantic sea surface temperature," but this warming trend "does not seem to influence the tropical storm activity."

This state of affairs seemed puzzling at first, because a warming of the tropical North Atlantic is known to reduce vertical wind shear there and thus promote the development of tropical storms. However, Latif *et al*.'s modeling work revealed a warming of the tropical Pacific enhances the vertical wind shear over the Atlantic, as does a warming of the tropical Indian Ocean. Consequently, they learned "the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic," and "apparently, the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity [has] remained rather stable and mostly within the range of the natural multidecadal variability."

A striking exception occurred in 2005 when, the researchers report, "the tropical North Atlantic warmed more rapidly than the Indo-Pacific," which reduced vertical wind shear over the North Atlantic, producing the most intense Atlantic hurricane season of the historical record. By contrast, they note the summer and fall of 2006 were "characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans," and "this explains the weak tropical storm activity [of that year]."

Clearly, the temperature/hurricane connection is nowhere near as "one-dimensional" as Al Gore and others make it out to be. Warming alone does *not* ensure hurricanes will get stronger. Instead, as Latif *et al*. describe it, "the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region." They note "changes in the meridional overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered" and "changes in ENSO statistics in the tropical Pacific may become important."

Scileppi and Donnelly (2007) note "when a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats," and long-term records of hurricane activity are thus formed "as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers." Based on this knowledge, they refined and lengthened the hurricane record of the New York City area by calibrating the sedimentary record of surrounding backbarrier environments to documented hurricanes—including those of 1893, 1821, 1788, and 1693—and extracting several thousand additional years of hurricane history from the sedimentary archive.

The two researchers determined "alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales." They point out "several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550–1850 AD) when sea surface temperatures were generally colder than present," and "no major hurricanes have impacted this area since 1893," when Earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

Noting Emanuel (2005) and Webster *et al*. (2005) had produced analyses suggesting "cooler climate conditions in the past may have resulted in fewer strong hurricanes," whereas their own findings suggest just the opposite, Scileppe and Donnelly conclude "other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower sea surface temperatures" prior to the development of the Current Warm Period.

Briggs (2008) developed Bayesian statistical models for the number of tropical cyclones, the rate at which these cyclones became hurricanes, and the rate at which the hurricanes became Category 4+ storms in the North Atlantic, based on data from 1966 to 2006. He concluded there is "no evidence that the distributional mean of individual storm intensity, measured by storm days, track length, or individual storm power dissipation index, has changed (increased or decreased) through time."

Chylek and Lesins (2008) applied "simple statistical methods to the NOAA HURDAT record of storm activity in the North Atlantic basin between 1851 and 2007 to investigate a possible linear trend, periodicity, and other features of interest." Noting "the last minimum in hurricane activity occurred around 1980," the two researchers compared the two 28-year-long periods on either side of this date and found "a modest increase of minor hurricanes, no change in the number of major hurricanes, and a decrease in cases of rapid hurricane intensification." Hence, they conclude "if there is an increase in hurricane activity connected to a greenhouse gas induced global warming, it is currently obscured."

Vecchi *et al*. (2008) note "a key question in the study of near-term climate change is whether there is a causal connection between warming tropical sea surface temperatures (SSTs) and Atlantic hurricane activity." They explain in more detail the two schools of thought on this topic: one posits the intensity of Atlantic Basin hurricanes is directly related to the absolute SST of the basin's main development region, which would be expected to rise in response to global warming, and the other posits Atlantic hurricane intensity is directly related to the SST of the Atlantic basin's main development region relative to the SSTs of the other tropical ocean basins, which could either rise or fall to a modest degree in response to global warming—and possibly even cycle between the two modes.

Vecchi *et al*. proceeded to plot Atlantic hurricane power dissipation index (PDI) anomalies calculated from both the absolute SST values of the Atlantic Basin and the relative SST values derived from all tropical ocean basins as a function of time, extending them throughout most of the current century based on projections of the two parameters obtained from 24 climate models. They compared the results they obtained for the period 1946–2007 with the measured PDI anomalies. They found the relative SST "is as well correlated with Atlantic hurricane activity as the absolute SST." They also report the "relative SST does not experience a substantial trend in 21st-century projections," and therefore, "a future where relative SST controls Atlantic hurricane activity is a future similar to the recent past, with periods of higher and lower hurricane activity relative to present-day conditions due to natural climate variability, but with little long-term trend."

Vecchi *et al*. say their work "suggests that we are presently at an impasse," and "many years of data will be required to reject one hypothesis in favor of the other," as the projections derived from the absolute and relative SST parameters "do not diverge completely until the mid-2020s." If the absolute SST ultimately proves to be the proper forcing factor, projections of more-intense Atlantic hurricanes would have some validity. But if the relative SST proves to be the controlling factor, the researchers note, "an attribution of the recent increase in hurricane activity to human activities is not appropriate, because the recent changes in relative SST in the Atlantic are not yet distinct from natural climate variability."

Climate modelers are not quite ready to throw in the towel, as evidenced from a recent report from Bender *et al*. (2010). They "explored the influence of future global warming on Atlantic hurricanes with a downscaling strategy by using an operational hurricane-prediction model that produces a realistic distribution of intense hurricane activity for present-day conditions," working with 18 models from the World Climate Research Program's Coupled Model Intercomparison Project 3 and employing the Intergovernmental Panel on Climate Change's A1B emissions scenario.

They found "an increase in the number of the most intense storms for the warmer climate compared with the control climate." Bender *et al*. predicted for "category 4 and 5 hurricanes with maximum winds greater than 60 m/s, the total number increased sharply from 24 to 46," and "hurricanes with winds greater than 65 m/s increased from 6 to 21." However, they also report there were reductions in the total number of hurricanes of all categories, which seems to contradict their own findings.

The researchers comment on the wide range of variability in the model predictions. They note, for example, an increase in hurricane-caused "damage potential" of +30% was projected for the 18-model ensemble, but a range of -50% to +70% was found for four models for which they did more detailed work. This extreme variability reduces confidence in their mean result.

Bender *et al*.'s findings clearly contradict the supposed link between the occurrence of strong hurricanes of the recent past with what many have claimed was unnatural and unprecedented CO_2-induced global warming. Quite to the contrary, and although the new model results suggest "a significant anthropogenic increase in the frequency of very intense Atlantic hurricanes may emerge from the background climate variability," the researchers say this development likely would not occur until "the latter half of the 21st century."

As is nearly always the case in climate modeling work, Kerr (2010) reports, in a commentary on Bender *et al*.'s study, that the researchers "are looking for yet more computer power and higher resolution to boost the realism of simulations." If those improvements are realized, and "if the models continue to converge as realism increases," Kerr writes, "the monster storms that seemed to be already upon us would be removed to decades hence."

But who really knows, when one is working with decidedly imperfect models of a complex planetary climate and weather system? As Kerr reports, even the researchers themselves "caution" their findings are still "far from the last word" on the subject.

Following up on an earlier paper (Chenoweth and Divine, 2008) in which they "presented a 318-year record of tropical cyclone activity in the Lesser Antilles and determined that there [was] no statistically significant change in the frequency of tropical cyclones (tropical storms and hurricanes) as well as tropical depressions over the entire length of the record," Chenoweth and Divine (2012) conducted a new analysis in which they examined the records employed in their earlier paper in more detail. They determined "the maximum estimated wind speed for each tropical cyclone for each hurricane season to produce a seasonal value of the total cyclone energy of each storm along various transects that pass through the 61.5°W meridian."

Somewhat analogous to accumulated cyclone energy (ACE), they calculated Lesser Antilles Cyclone Energy (LACE) along a fixed spatial domain (10–25°N, 61.5°W) at any time a tropical cyclone passed through it, after which they performed spectral and wavelet analysis on the LACE time series and tested it for statistical significance of trends. Chenoweth and Divine report their record of tropical cyclone activity "reveals no trends in LACE in the best-sampled regions for the past 320 years," and "even in the incompletely sampled region north of the Lesser Antilles there is no trend in either numbers or

LACE.” In addition, they note LACE along the 61.5°W meridian is “highly correlated” with Atlantic-Basin-wide ACE, suggesting their findings may extend beyond their region of study.

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7.8.1.3 El Niño Effect

How do Atlantic basin hurricanes respond to increases in temperature? In exploring this question within the context of the warming that occurs in going from cooler La Niña conditions to warmer El Niño conditions, Wilson (1999) analyzed data from the last half of the twentieth century, finding the probability of having three or more intense hurricanes was only 14% during a (relatively) warm El Niño year, but fully 53% during a (relatively) cool La Niña year. Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone the average ranged from 1.7 per La Niña season to 0.5 per El Niño season, a frequency-of-occurrence decline of fully 70% in going from cooler La Niña conditions to warmer El Niño conditions. Elsner *et al*. (2001), who also worked with data from the entire past century, also found "the probability of a U.S. hurricane increases" when there are below-normal sea surface temperatures in the equatorial Pacific.

Lyons (2004) conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three groupings: the 10 highest storm and hurricane landfall years, the nine lowest such years, and all other years. These groupings revealed, in Lyons' words, "La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years," and "El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years." In addition, "La Niña (El Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years."

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. They first determined 22 years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. They compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a 10-year study carried out on the other side of the Atlantic, Brichetti *et al*. (2000) determined, contrary to their own expectation, that survival rates for a Mediterranean water bird (Cory's Shearwater) were greater during warmer El Niño years than during cooler La Niña years.

Landsea *et al*. (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991–1994) that had exhibited the lowest such activity since the keeping of reliable records began. They determined the most important factor behind this transition was what they called the "dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions."

In a twentieth century changepoint analysis of time series of major North Atlantic and U.S. annual hurricane counts, which Elsner *et al*. (2004) say "quantitatively identifies temporal shifts in the mean value of the observations," the authors found "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

As for why North Atlantic hurricane activity is suppressed under warmer El Niño conditions, Donnelly and Woodruff (2007) opined it was "due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development." Such a conclusion is supported by the results of two analyses conducted by Klotzbach. Klotzbach (2011a) examined Caribbean tropical cyclone activity over the period 1900–2008, looking for impacts from the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). He found "the probability of one or more hurricanes and major hurricanes tracking through the Caribbean increases dramatically from 39% and 26% in the 10 warmest ENSO years to 92% and 63% in the 10 coldest ENSO years, respectively," in harmony with the similar findings of Tartaglione *et al*. (2003), who additionally demonstrated this cooling-induced response was likely due to "reductions in vertical wind shear and increases in low-level vorticity" in La Niña conditions. This connection also was demonstrated by Klotzbach, who determined "for the 10 warmest events since 1948, the average 200–850-mb zonal wind shear in the Caribbean was 7 m/s compared with only 3 m/s in the 10 coldest events since 1948."

The Colorado State University researcher also determined "the impacts of ENSO are reduced slightly when the AMO is positive," and he found "a negative AMO phase and El Niño combine to provide large-scale climate features that are especially hostile for tropical cyclones." He reports, for example, "29 hurricanes tracked into the Caribbean in the 10 strongest La Niña years in a positive AMO period compared with only two hurricanes tracking through the Caribbean in the 10 strongest El Niño years in a negative Atlantic multidecadal oscillation period."

Similar findings were reported in Klotzbach's second paper (2011b), which expanded his analysis beyond the Caribbean and throughout the Atlantic basin.

In addition to the growing body of empirical evidence that indicates global warming has little or no impact on the intensity of hurricanes, there exists model-based evidence for the same conclusion. Vecchi and Soden (2007), for example, explored "21st Century projected changes in VS [vertical wind shear] over the tropical Atlantic and its ties to the Pacific Walker circulation, using a suite of coupled ocean-atmosphere models forced by emissions Scenario A1B (atmospheric CO_2 stabilization at 720 ppm by year 2100) for the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4)," where VS was defined as "the magnitude of the vector difference between monthly-mean winds at 850 hPa and 200 hPa," and where "changes are computed between two 20-year periods: 2001–2020 and 2081–2100."

The analysis revealed the 18-model ensemble-mean projected change in VS over the twenty-first century is "a prominent increase in VS over the topical Atlantic and East Pacific (10°N–25°N)." Noting "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," they state the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century," and "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America."

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7.8.2 Indian Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Indian Ocean.

Hassim and Walsh (2008) analyzed tropical cyclone (TC) best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) for the presence of systematic intensity and duration trends over the cyclone season from 1969–1970 through 2004–2005. Their results indicated "the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones [increased] since 1980." A contemporaneous study of roughly the same region and time period by Harper *et al*. (2008) yielded a much different result.

Harper *et al*. analyzed several "potential influences on the accuracy of estimating TC intensity over time due to increasing technology, methodology, knowledge and skill" for TCs that occurred off the coast of northwestern Australia, primarily in a band between 5 and 25°S, over the period 1968–1969 to 2000–2001. The four Australian researchers show "a bias towards lower intensities likely exists in earlier (mainly pre-1980) TC central pressure deficit estimates of the order of at least 20% in 1970, reducing to around ten% by 1980 and to five% in 1985." They report "inferred temporal trends in the estimated intensity from the original data-sets are therefore significantly reduced in the objectively reviewed data-set." Thus they conclude "there is no prima facie evidence of a potential climate-change induced trend in TC intensity in northwestern Australia over the past 30 years."

Similar findings were reported two years later by Goebbert and Leslie (2010), who examined interannual TC variability of the northwest Australian (NWAUS) sub-basin of the southeastern Indian

Ocean (0–35°S, 105°–135°E) over the 39-year time period 1970–2008, using the Woodside Petroleum Ltd. reanalysis TC dataset described by Harper *et al*. (2008). The two researchers could find "no significant linear trends in either mean annual TC frequencies or TC days" and "no trend in the number of intense TCs for the NWAUS sub-basin." They note "none of the 13 NWAUS TC metrics exhibited statistically significant linear trends." They conclude, "known climate indices—such as Niño-3.4, Niño-4, SOI, NOI, PDO, NAO, and others—generally were found not to be significantly correlated to the variability of TC frequency or TC days in the NWAUS region."

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed "the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." Regarding the southeast Indian Ocean, for example, Hall determined "the overall number of depressions and tropical cyclones was below the long-term mean." Further east, he found broad-scale convection was near or slightly above normal, but "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which represented "a continuation of the trend of the previous few seasons." Hall's work, like that of Harper *et al*. (2008) and Goebbert and Leslie (2010), suggests a likely decline in both the intensity and frequency of Indian-Ocean tropical cyclones if the world warms in the future.

Singh *et al*. (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877–1998. The planet was recovering from the global chill of the Little Ice Age at this time, making it logical to assume their findings would be indicative of changes in hurricane characteristics that might be expected if Earth were to warm by that amount again, which is what the IPCC models project it will do.

On an annual basis, Singh *et al*. report there was a slight decrease in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one fewer hurricane per year at the end of the 122-year record in 1998 than at its start in 1877. In addition, based on data from the Bay of Bengal, they found tropical cyclone numbers dropped during the months of most severe cyclone formation (November and May) when the El Niño-Southern Oscillation was in a warm phase. In light of these observations, it would appear that if tropical cyclones of the North Indian Ocean were to change at all in response to global warming, their overall frequency and the frequency of the most intense such storms would likely decrease, just the opposite of what climate models typically suggest will occur.

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world and specifically the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report for the period 1891–1997 there was a significant decreasing trend (at the 99% confidence level) in the frequency of cyclones with the designation of "cyclonic storm" and above, and "the maximum decrease was in the last four decades," citing the work of Srivastava *et al*. (2000). In addition, they note Singh and Khan (1999) also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

Raghavan and Rajesh say "there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change." However, they continue, "studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones." Thus they confidently state "the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular media and even in some more serious publications, does not therefore have a sound scientific basis."

Kumar and Sankar (2010) say "an important concern about the consequences of the global warming scenario is its impact on the frequency, the intensity, and the duration of tropical cyclones," noting "theoretical and modeling studies indicate that tropical cyclone winds would increase with increasing ocean temperature." To see to what extent the implications of these theoretical model studies harmonize with what actually occurred throughout the North Indian Ocean over the period 1901–2007, Kumar and Sankar employed "various datasets, such as the NCEP/NCAR Reanalysis dataset, the ERSST and the tracks of storms and depressions over the north Indian Ocean for different seasons based on the period 1901–2007," comparing "changes that occurred during the period 1951–2007 and the previous period, 1901–1951." They also compared the sub-period 1951–1978 (epoch I) with the sub-period 1979–2007 (epoch II).

The two researchers determined "the frequency of storms and severe storms do not show a dramatic rise in spite of a substantial increase in the sea surface temperature in the Bay of Bengal from 1951–2007 compared to 1901–1951." Also, while noting "the Bay of Bengal has been warming throughout the year during epoch II compared to epoch I," they report "the number of both storms and severe storms, have decreased largely over the Bay of Bengal." Such findings, they write, "clearly indicate that warm SST's alone are not sufficient for the initiation of convective systems over the Arabian Sea and the Bay of Bengal," noting their results suggest a "decreasing trend in the frequency of storms over the Bay of Bengal, contrary to the popular belief that there will be an increase."

The authors note "in the current debate on global warming and the change in the number of intense cyclones, initial studies carried out have shown very different results for the northern Indian Ocean," where, as they describe it, "Webster *et al*. (2005) found that there had been a considerable increase in the number of categories 4 and 5 cyclones with a maximum sustained wind reaching at least 115 knots." They note, however, Landsea *et al*. (2006) subsequently demonstrated the databases employed by Webster *et al*. "were not sufficiently reliable," as "cyclones archived as being categories 2 or 3 had been re-analyzed and assigned as categories 4 or 5." They also note, "Kossin *et al*. (2007) did not note any trend towards an increase in the number of categories 4 and 5 cyclones in the northern Indian Ocean for their period of analysis, which covered from 1983 to 2005."

Hoarau *et al*. (2012) analyzed intense cyclone activity in the northern Indian Ocean from 1980 to 2009 on the basis of a homogenous reanalysis of satellite imagery. The three French researchers conclude "there has been no trend towards an increase in the number of categories 3–5 cyclones over the last 30 years," noting "the decade from 1990 to 1999 was by far the most active with 11 intense cyclones while 5 intense cyclones formed in each of the other two decades"; i.e., those that preceded and followed the 1990s. They state there has "not been a regular increase in the number of cyclone 'landfalls' over the last three decades (1980–2009)."

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7.8.3 Pacific Ocean

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the Pacific Ocean.

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that originated in or entered the central North Pacific (0–70°N, 140–180°W) over the 32-year period 1966–1997. They found "tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise." This increase appears to have been due to a step-change that led to the creation of "fewer cyclones during the first half of the record (1966–81) and more during the second half of the record (1982–1997)." Accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity.

Although these findings may appear to support model-based projections that CO_2-induced global warming leads to more frequent and stronger hurricanes, Chu and Clark state the observed increase in tropical cyclone activity cannot be due to CO_2-induced global warming, because, in their words, "global warming is a gradual process" and "it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s."

A much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark and their relationship to mean global air temperature. The beginnings of such a history were presented by Liu *et al*. (2001), who waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975.

Calibrating the historical data against instrumental observations over the period 1884–1909, they found the trends of the two datasets were significantly correlated (r = 0.71), and this observation led them to conclude "the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls." They conducted a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that "suggests an external forcing mechanism, which remains to be identified." Also, and importantly, they found "the two periods of most frequent typhoon strikes in Guangdong (AD 1660–1680, 1850–1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age."

Hayne and Chappell (2001) studied a series of storm ridges at Curacoa Island, deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events affecting that area, with one of their stated reasons for doing so being to test the climate-model-based hypothesis that "global warming leads to an increase of cyclone frequency or intensity." They found "cyclone frequency was statistically constant over the last 5,000 years," and they could find "no indication that cyclones have changed in intensity."

Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S, by geologically dating and topographically surveying landform features left by historic hurricanes and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred during the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of their study. They also report the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The twentieth century was totally devoid of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

Noting "many researchers have suggested that the buildup of greenhouse gases (Watson *et al*., 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs)," Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data. They explain, "if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades."

Focusing on the last four decades of the twentieth century, they found a number of parameters related to SST and TC activity in the Western North Pacific (WNP) "have gone through large interannual as well as interdecadal variations," and "they also show a slight decreasing trend." In addition, they write, "no significant correlation was found between the typhoon activity parameters and local SST." They write, "in other words, an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models."

Chan and Liu suggest the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere. "In other words," they state, "the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999)," whereas "in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process." They conclude, "at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs."

Free *et al*. (2004) looked not for increases in actual hurricane intensity, but instead for increases in potential hurricane intensity, because "changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." They used radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific and Atlantic Oceans and compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." Between 1975 and 1980, they further report, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001–2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This analysis indicated "the 2001–2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, "the overall number of depressions and tropical cyclones was below the long-term mean." Further east he found broad-scale convection was near or slightly above normal, but "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which represented "a continuation of the trend of the previous few seasons." Hall writes, "in the eastern Australian region, the four-year period up to 2001–2002 was by far the quietest recorded in the past 41 years."

Noting Emanuel (2005) and Webster *et al*. (2005) had claimed "tropical cyclone intensity has increased markedly in recent decades" and "tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming," Ren *et al*. (2006) analyzed tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced torrential precipitation events. They report "significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years." They also state the downward trends were accompanied by "decreases in the numbers of TCs and typhoons that affected China during the period 1957–2004." In a conclusion that differs dramatically from the claims of Emanuel (2005) and Webster *et al*. (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al*. say their findings "strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP."

Wu *et al*. (2006) ran two independent checks on Webster *et al*.'s findings by performing analyses of best track data from the Regional Specialized Meteorological Centre (RSMC) Tokyo (Japan) and from the Hong Kong Observatory (HKO; Hong Kong, China). This work revealed, "in contrast to Webster *et al*.'s findings, there was no increase in western North Pacific category 4–5 typhoon activity," and "neither RSMC-Tokyo nor HKO best track data suggest an increase in western North Pacific tropical cyclone destructiveness as measured by the potential destructive index (PDI)," in contrast to the findings of Emanuel (2005).

Wu *et al.* state the RSMC-Tokyo data "show a decrease in the proportion of category 4–5 typhoons from 18% to 8% between the two periods 1977–1989 and 1990–2004," noting "the result is the same if the analysis is extended to include 2005" and the trend is "statistically significant at the 5% level." In addition, they report "HKO best track data show a decrease in the proportion of category 4–5 typhoons, from 32% to 16%, between 1975–1989 and 1990–2004," noting this result too is "statistically significant at the 5% level" and it also "remains unchanged if the end year is extended to 2005."

Nott *et al*. (2007) developed a 777-year-long annually resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. They found "the period between AD 1600 to 1800"—when the Little Ice Age held sway throughout the world—"had many more intense or hazardous cyclones impacting the site than the post AD 1800 period," when the planet gradually began to warm. The four researchers point out "the only way to determine the likely future behavior of tropical cyclones is to first understand their history from high resolution records of multi-century length or greater."

Li *et al*. (2007) analyzed tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949–2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951–2003. They used their empirical findings to infer future tropical cyclone activity in the region based on climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed there were "more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present." They further found "the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones."

Based on simulations of future occurrences of these favorable and unfavorable conditions derived from "a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios," they then determined "the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it."

Chan (2007) searched for "possible physical causes responsible for the interannual variations of the activity of intense typhoons in the WNP [Western North Pacific] (here defined as the region 0–40°N, 120–180°E)." The City University of Hong Kong researcher reports "in years with a high frequency of occurrence of intense typhoons, both the dynamic (relative vorticity in both the lower and upper troposphere as well as the vertical wind shear) and thermodynamic (as represented by the moist static energy in the low to mid troposphere) conditions in the atmosphere, especially in the eastern part of the WNP, are favorable for the formation of TCs [tropical cyclones]," and "once formed, these TCs tend to have longer lifetimes over the ocean, and therefore have a high chance to become more intense." In addition, he notes the factors responsible for increasing the number of strong TCs are "also significantly correlated with the Niño3.4 SST anomalies." Consequently, Chan reports, "the frequency of occurrence of intense typhoons in this region is not likely determined by the average SST over the region," which is what would be expected to increase in response to greenhouse gas-induced global warming. Chan's primary finding—that "interannual variations of intense typhoons in the WNP are likely caused to a large extent by changes in the planetary-scale atmospheric circulation and thermodynamic structure associated with the El Niño phenomenon"—provides no support for the contentions of either Emanuel (2005) or Webster *et al*. (2005).

Nott (2007) notes, "in tropical Australia, palaeo-tropical cyclone records occur in the form of low-resolution millennial-scale sedimentary ridges and high-resolution centennial-scale stalagmite records of isotopically depleted tropical cyclone rainfall." He recounts the findings of those records and discusses their relevance to risk assessment and their role in "decoupling human induced changes in cyclone behavior from natural variability." He states the clear message of the several papers he reviews is "the historical/instrumental record substantially underestimates the frequency of the most extreme tropical cyclone events," citing the findings of Chappell *et al*. (1983), Chivas *et al*. (1986), Hayne and Chappell (2001), Nott and Hayne (2001), and Nott *et al*. (2007). He notes "tropical cyclone activity in north-east Queensland has been in a phase of quiescence since before European settlement of the region" and "the period between AD 1600 and 1800 [during the Little Ice Age] had many more intense or hazardous cyclones impacting the site than the post AD 1800 period."

In addition, Nott notes the first 200 years of the tropical cyclone record—from AD 1200 to 1400, which represents the latter part of the Medieval Warm Period (MWP)—had the fewest intense cyclones. According to the criterion he used to define them, this period of significant global warmth had none, as did the latter decades of the twentieth century. He found the entire twentieth century had but one such intense cyclone, in 1911, whereas there were as many as seven intense tropical cyclones during the global chill that prevailed between AD 1600 and 1800.

Chan (2008) further investigated possible causes of the multidecadal variability in intense TC [category 4 and 5] occurrence in the WNP, choosing this basin because it generally has the largest number of TCs each year. Based on data for the period 1960–2005, he determined decadal variations in intense typhoon activity largely resulted from a combination of the behavior of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). This finding led him to suggest "the view that global warming would lead to more intense TCs owing to the enhancement of thermodynamic factors ignores the fact that for TCs to intensify significantly, the dynamic factors must 'cooperate,'" which he notes has not been demonstrated to occur basin-wide. Therefore, he continues, "the more likely conclusion is that the major low-frequency variations in the frequency of intense TC occurrence is probably a multi-decadal one in response to similar variations in the factors that govern the formation, intensification and movement of TCs," and "such variations largely result from modifications of the atmospheric and oceanographic conditions in response to ENSO and PDO." Consequently, "at least for the WNP," Chan notes, "it is not possible to conclude that the variations in intense typhoon activity are attributable to the effect of global warming."

Defining rapid intensification (RI) of a tropical cyclone as occurring when the maximum wind speed of a TC "reaches at least (a) 5 knots in the first 6 hours, (b) 10 knots in the first 12 hours, and (c) 30 knots in 24 hours," Wang and Zhou (2008) state "all category 4 and 5 hurricanes in the Atlantic basin and 90% of the equivalent-strength typhoons in the western North Pacific experience at least one RI process in their life cycles." Using best-track TC data obtained from the Joint Typhoon Warning Center for the 40-year period 1965–2004, Wang and Zhou determined the climatic conditions most critical for the development of RI in TCs of the Western North Pacific on annual, intra-seasonal, and interannual time scales. They found "over the past 40 years, the annual total of RI in the western North Pacific shows pronounced interdecadal variation but no significant trend," and they note this "implies that the super typhoons had likely no upward trend in the last 40 years." In addition, they found "when the mean latitude, where the tropical storms form, shifted southward (either seasonally or from year to year), the proportion of super typhoons or major hurricanes will increase," noting "this finding contrasts the current notion that higher sea surface temperature leads to more frequent occurrence of category 4 or 5 hurricanes."

Englehart *et al*. (2008) developed a "first cut" dataset pertaining to the area immediately adjacent to Mexico's Pacific coast. Although noting only 54% of the total number of Eastern Pacific storms reached TC status within this near-shore area over the period 1967–2005, they report "near-shore storm activity is fairly well correlated with total basin TC activity, a result which suggests that over the longer period (i.e., 1921-onward), changes in near-shore activity can provide some sense of the broader basin activity." Their study revealed the existence of significant decadal variability in annual eastern Pacific near-shore TC frequency of occurrence. In addition, they found "long-term TC frequency exhibits a significant ($p = 0.05$) negative trend," which, as best can be determined from their graph of the data, declines by about 23% over the 85-year period 1921–2005. This result was driven solely by an approximate 30% drop in TC frequency during the late (August–November) TC season, with essentially no long-term trend in the early (May–July) TC season.

Englehart *et al.* present a graph of the maximum wind speed associated with each TC, from which one can calculate an approximate 20% decline in this intensity-related parameter over the period of their study. Their work provides no support for the claim that global warming increases the frequency and intensity of TCs and/or hurricanes.

Hassim and Walsh (2008) analyzed TC best track data pertaining to severe storms of the Australian region (5–30°S) forming off Western Australia and the Northern Territory (the western sector: 90–135°E, Indian Ocean) and off Queensland and the Gulf of Carpentaria (the eastern sector: 135–160°E, Pacific Ocean) for the presence of systematic intensity and duration trends over the cyclone season periods running from 1969–1970 through 2004–2005. The two Australian researchers report "substantial differences in trends are found between the two sub-regions, with the number, average maximum intensity, and duration at the severe category intensities of tropical cyclones increasing since 1980 in the west but decreasing (in number) or exhibiting no trend (in intensity, severe category duration) in the east."

Lu *et al*. (2008) also studied Western North Pacific (WNP) TCs during this time period, noting the WNP "is an area where typhoon activity is the most frequent and strongest" and "China is one of the countries that seriously suffered from typhoons in this area." Using TC data "in the yearbooks of TC of the WNP from 1960 to 2005," they analyzed the interdecadal variation of WNP TCs and the large-scale circulation factors affecting them. This analysis revealed "the time period from 1960 to 2005 has two high frequency periods (HFPs) and two low frequency periods (LFPs)," with the overall trend being downward (see Figure 7.8.3.1).

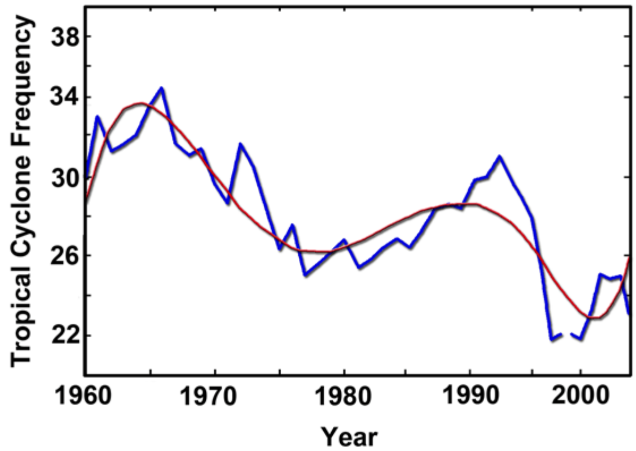

Figure 7.8.3.1. Tropical cyclone frequency vs. year. Blue line represents five-year running means, while the red line is a fifth-order polynomial that has been fitted to the data points. Adapted from Lu, Q-z., Hu, B-h., Wang, J. and Zhang, Y. 2008. Impact of large-scale circulation on the interdecadal variations of the western North Pacific tropical cyclone. *Journal of Tropical Meteorology* **14**: 1006–8775(2008) 01-0081-04.

One year later, noting "the variability of TC activity (including the frequency of occurrence and intensity) has become a great concern because it may be affected by global warming," Kubota and Chan (2009) created a unique dataset of TLP (tropical cyclone landfall numbers in the Philippines) based on historical observations of TC tracks during the period 1901–1940 obtained from monthly bulletins of the Philippine Weather Bureau and combined with TLP data obtained from the Joint Typhoon Warning Center for the period 1945–2005, which they used to investigate the TC-global warming hypothesis. The two Asian researchers found "the TLP has an apparent oscillation of about 32 years before 1939 and an oscillation of about 10–22 years after 1945," but "no long-term trend is found." In addition, they determined "natural variability related to ENSO and PDO phases appears to prevail in the interdecadal variability of TLP," and their results show all variability was merely oscillatory activity around a mean trend of zero slope (see Figure 7.8.3.2).

Ma and Chen (2009) used NCEP/NCAR reanalysis data to determine the SST distribution over this region and to evaluate its temporal variability, utilizing TC frequency data obtained from the Joint Typhoon Warning Center, the *Tropical Cyclone Year Book* of the China Meteorological Administration, and the Tokyo-Typhoon Center of the Japanese Meteorological Agency to characterize TC frequency over the period 1949–2007. This work revealed, "SSTs over the WNP have been gradually increasing during the past 60 years ... with a maximum increment of 1°C around the central equatorial Pacific for the last 10 years." They also state "the warm pool, which is defined to be enclosed by a critical temperature of 28°C, has expanded eastward and northward in recent years," noting further "there has been remarkable warming in the last decade, more than 0.8°C in some local areas." Nevertheless, and in spite of this "remarkable warming," the two researchers determined "the frequency of TC against the background of global warming has decreased with time."

Chan and Xu (2009) used TC data obtained from the Joint Typhoon Warning Center for the period 1945–2004 and the *Annual Tropical Cyclone Data Book* (edited by the Shanghai Typhoon Institute) for the period 1951–2000 to conduct a comprehensive study of variations in the annual number of landfalling TCs in three sub-regions of East Asia: South (south China, Vietnam, and the Philippines),

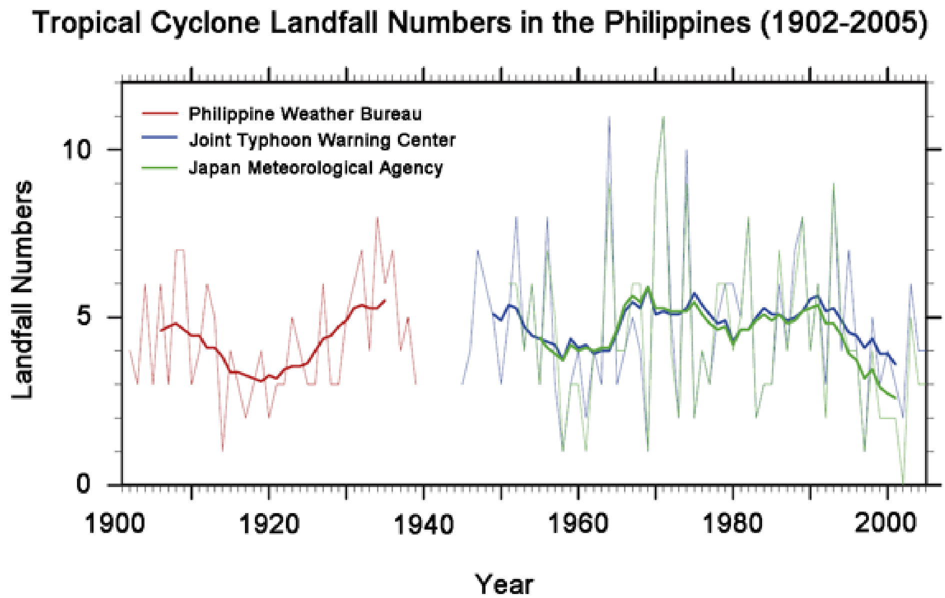

Figure 7.8.3.2. Tropical cyclone landfall numbers in the Philippines over the period 1902-2005. Adapted from Kubota, H. and Chan, J.C.L. 2009. Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. *Geophysical Research Letters* **36**: 10.1029/2009GL038108.

Middle (east China), and North (Korean Peninsula and Japan). They report "wavelet analyses of each time series show that the landfalling frequencies go through large inter-annual (2–8 years), inter-decadal (8–16 years) and even multi-decadal (16–32 years) variations, with the inter-annual being the most dominant, and the multi-decadal explaining most of the rest of the variance." In what they call "an important finding," they state "none of the time series shows a significant linear temporal trend, which suggests that global warming has not led to more landfalls in any of the regions in Asia."

Song *et al*. (2010) point out, "in recent years, there has been increasing interest in whether global warming is enhancing tropical cyclone (TC) activity," as has been claimed by Emanuel (2005) and Webster *et al*. (2005). They note Wu *et al*. (2006) and Yeung (2006) found "no increase in category 4–5 typhoon activity in the western North Pacific basin," "in contrast to Webster *et al*. (2005)."

In addition, Song *et al*. report "neither RSMC nor HKO best track data suggest an increase in TC destructiveness." They further state "other studies also examined the differences in TC data sets from the Joint Typhoon Warning Center (JTWC) of the U.S. Naval Pacific Meteorology Oceanography Center in Hawaii, the RSMC, and the Shanghai Typhoon Institute (STI) of [the] China Meteorological Administration in Shanghai (Lei, 2001; Kamahori *et al*., 2006; Ott, 2006; Yu *et al*., 2007)," and "so far, the reported trends in TC activity in the WNP basin have been detected mainly in the JTWC best track data set," which was the one employed by Emanuel (2005) and Webster *et al*. (2005) in drawing their anomalous conclusions.

To help resolve the anomalies exhibited by the JTWC typhoon database, Song *et al*. analyzed differences in track, intensity, frequency, and the associated long-term trends of those TCs that were simultaneously recorded and included within the best track data sets of the JTWC, the RSMC, and the STI from 1945 to 2007. They determined "though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2–3 as category 4–5, leading to an upward trend in the annual frequency of category 4–5 TCs and the annual accumulated power dissipation index, as reported by Webster *et al*. (2005) and Emanuel (2005)." They state "this trend and potential destructiveness over the period 1977–2007 are found only with the JTWC data set," while noting downward trends "are apparent in the RSMC and STI data sets."

Fengjin and Ziniu (2010) used data obtained from the China Meteorological Administration on the time and site of TC generation and landfall, TC tracks, and the intensity and duration of TCs in the WNP and China for the period 1951–2008 to analyze the characteristics of TCs making landfall in China over that period. This work revealed "a decreasing trend in the generation of TCs in the WNP since the 1980s," and they note the number of TCs making landfall during this period "has remained constant or shown only a slight decreasing trend." They also report "the number of casualties caused by TCs in China appears to show a slight decreasing trend.

Terry and Gienko (2010) analyzed various cyclone characteristics based on four decades of cyclone season data (1969–1970 to 2007–2008) in the regional cyclone archive of the tropical South Pacific (160°E–120°W, 0°–25°S) maintained by the Regional Specialized Meteorological Centre (RSMC) located at Nadi in the Fiji Islands. They state "no linear trends were revealed in cyclogenesis origins, cyclone duration, track length or track azimuth over the four decades of records," but "anomalous activity for one or more cyclone parameters occurred in 1976, 1981, 1983, 1991, 1998, 2001–2002 and 2003," leading them to conclude "there is as yet no evidence for climate-change forcing of these storm characteristics over recent historical times."

Sun *et al*. (2011) analyzed data pertaining to TCs over the northwestern Pacific and the South China Sea, obtained from China's Shanghai Typhoon Institute and the National Climate Center of the China Meteorological Administration, pertaining to the period 1951 to 2005. They determined the frequency of all TCs impacting China "tended to decrease from 1951 to 2005, with the lowest frequency [occurring] in the past ten years" (see Figure 7.8.3.3). In addition, they state the average yearly number of super typhoons was "three in the 1950s and 1960s" but "less than one in the past ten years." They write "the decrease in the frequency of super typhoons, at a rate of 0.4 every ten years, is particularly significant (surpassing the significance test at the 0.01 level)" (see Figure 7.8.3.4), adding "there is a decreasing trend with the extreme intensity of these TCs during the period of influence in the past 55 years."

Callaghan and Power (2011) developed and used "a new data base of severe land-falling TCs for eastern Australia derived from numerous historical sources, that has taken over a decade to develop." This database, they continue, includes "peer-reviewed publications; Bureau of Meteorology publications, including comprehensive case histories for a large number of TCs – including all TCs since the mid-1950s, *Monthly Climatological Bulletins* and *Monthly Weather Reviews*, unpublished TC season reports, bounded operational analysis charts back to the 1890s stored in the National Archives, unpublished internal Bureau documents; publications by state and local governments; archives of several Queensland newspapers; newspaper clippings held by the Bureau of Meteorology; books describing land-falling TCs; information held by the Cairns and Townsville Historical Societies; a report to the QLD parliament (1918); and extensive unpublished information from the public including numerous damage photographs," as well as "reports on storm surge, wave action and shipwreck data from an extensive Australian shipwreck data base."

The two researchers with Australia's Bureau of Meteorology note their new database allows them "to document changes over much longer periods than has been done previously for the Southern Hemisphere." Among the host of results they describe, two of them stand out with respect to their significance to the global warming debate. First, they report "the sign and magnitude of trends calculated over 30 years periods vary substantially," noting "caution needs to be taken in making inferences based on *e.g.* satellite era data only." Second, they report "the linear trend in the number of severe TCs making land-fall over eastern Australia declined from about 0.45 TC/year in the early 1870s to about 0.17 TC/year in recent times—a 62% decline." They note "this decline can be partially explained by a weakening of the Walker Circulation, and a natural shift towards a more El Niño-dominated era." Thus they conclude the abstract of their paper by saying, "the extent to which global warming might also be partially responsible for the decline in land-falls—if it is at all—is unknown," suggesting global warming might be doing just the opposite of what climate models typically suggest it should do.

Noting the Intergovernmental Panel on Climate Change (IPCC, 2001, 2007) has twice suggested "precipitation and extreme winds associated with tropical cyclones may have become more intense," Ying *et al*. (2011) remind us this claim is "mainly based on numerical models." Working with tropical cyclone best track and related observational severe wind and precipitation datasets created by the Shanghai Typhoon Institute of the China Meteorological Administration, the four researchers identified trends in observed TC characteristics over the period 1955 to 2006 for the whole of China and four sub-regions: South China (SC), comprising Guangdong, Guangxi, and Hainan Provinces; East

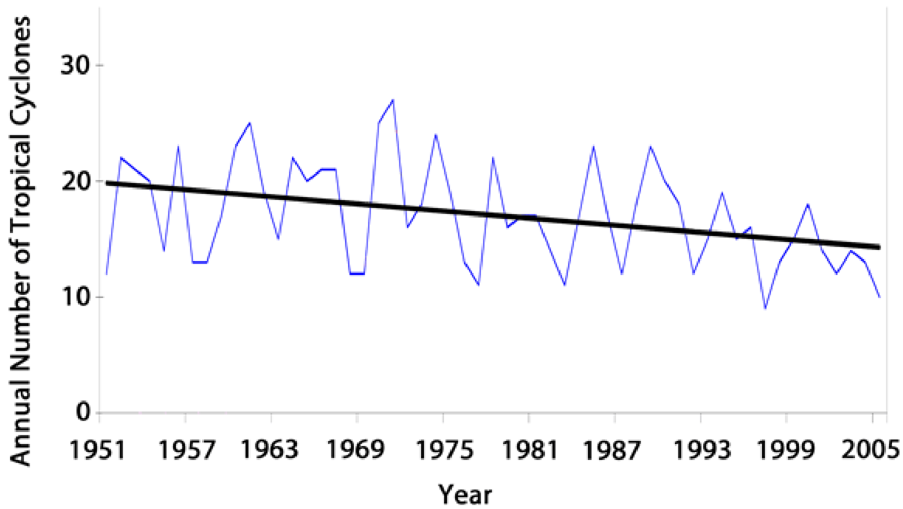

Figure 7.8.3.3. Number of typhoons affecting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* **17**: 181-186.

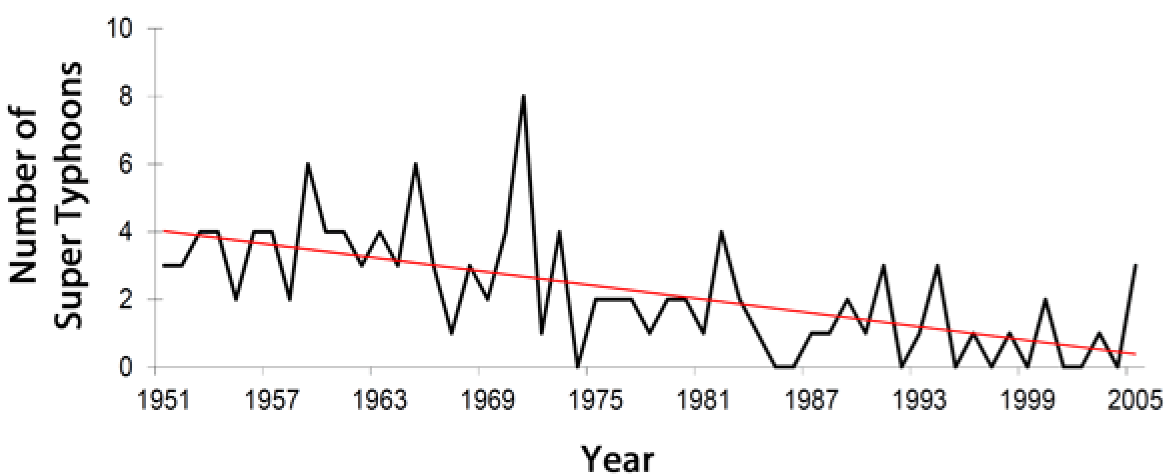

Figure 7.8.3.4. Frequency of super typhoons impacting China (1951-2005). Adapted from Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* **17**: 181-186.

China (EC), comprising Fujian, Hiangxi, Zhejiang, Anhui, Jiangsu, and Shandong Provinces plus Shangahi; Northeast China (NEC), comprising Liaoning, Jilin, and Heilongjiang Provinces; and China's inland area (CI) including all remaining provinces.

They found over the past half-century there have been no changes in the frequency of TC occurrence, except within NEC, where they determined "years with a high frequency of TC influence have significantly become less common." They also note, "during the past 50 years, there have been no significant trends in the days of TC influence on China" and "the seasonal rhythm of the TC influence on China also has not changed." They found "the maximum sustained winds of TCs affecting the whole of China and all sub-regions have decreasing trends" and "the trends of extreme storm precipitation and 1-hour precipitation were all insignificant." Thus, for the whole of China and essentially all of its component parts, major measures of TC impact have remained constant or slightly decreased, a much different consequence from what the IPCC has been predicting for the world over the past decade or more.

Xiao *et al*. (2011) "developed a Tropical Cyclone Potential Impact Index (TCPI) based on the air mass trajectories, disaster information, intensity, duration and frequency of tropical cyclones," using observational data obtained from the China Meteorological Administration's *Yearbook of Tropical (Typhoon) Cyclones in China* for the years 1951–2009 plus the *Annual Climate Impact Assessment* and *Yearbook of Meteorological Disasters* in China, also compiled by the China Meteorological Administration, but for the years 2005–2009. The five researchers report "China's TCPI appears to be a weak decreasing trend over the period [1949–2009], which is not significant overall, but significant in some periods."

Ren *et al*. (2011) write "the homogeneity of historical observations is important in the study of tropical cyclones and climate change," with "a large hurdle for climate change detection" being "the quality of TC historical databases," which they say "were populated over time without a focus on maintaining data homogeneity," "a key requirement for databases that are used to assess possible climate-related trends." In an effort to overcome this hurdle, which they describe as "a 'bottleneck' in tropical cyclone and climate change studies," Ren *et al*. analyze three historical datasets for Western North Pacific TCs—those of the Joint Typhoon Warning Center (JTWC), the Japan Meteorological Agency (JMA), and the China Meteorological Administration (CMA)—focusing primarily on TC intensity and covering the 55-year period 1951–2005.

The five researchers conclude "it is still difficult to judge which one [of the three datasets] is best." They indicate frequencies of the common TCs in all three datasets "show no obvious increasing or decreasing trend over the past 50 years." Instead, they find a weak interdecadal variation with "more TCs from the mid-1960s to the mid-1970s and in the early 1990s." By contrast, they state the intensities of the common TCs "differed largely from one dataset to another, leading to quite opposite conclusions for TCs of category 4 and 5." For example, they note "for the period after 1970, the JTWC dataset shows an increasing trend that complies with those of Webster *et al*. (2005) and Emanuel (2005)," but "for a longer time scale, the result may be well consistent with that of Chan (2006)," which suggests "the so-called 'trend' is a fragment of the longer inter-decadal variation."

Zhang *et al*. (2011) analyzed both the frequency and intensity of TCs that made landfall on the Pacific coast of South China's Guangdong Province between 1965 and 2007. Employing data extracted from the database collected by the Shanghai Typhoon Institute of the China Meteorological Administration, together with pertinent sea surface temperature (SST) data for the Pacific Ocean obtained from the UK Met Office's Hadley Centre, the four Chinese researchers studied the changing properties of the frequency and intensity of the TCs making landfall at the Guangdong Province (TMLGP) as functions of time and temperature.

They found the frequency of TMLGP after 1996 had "a nearly opposite trend compared to the period preceding 1996" and determined "the frequency of TMLGP for the period 1965–2007 as a whole is in an insignificant relation with SST in these two periods." They also found various SST measures "only have a weak influence on TMLGP intensities." They note, "despite the long-term warming trend in SST in the Western North Pacific, no long-term trend is observed in either the frequency or intensities of TMLGP."

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7.8.4 Global

As indicated in the introduction of Section 7.10, data presented in numerous peer-reviewed studies do not support the model-based claim that CO_2-induced global warming is causing (or will cause) more frequent or more severe tropical cyclones, or hurricanes. This subsection highlights such research as it pertains to the entire globe.

Climate models have long suggested the intensity and frequency of hurricanes or tropical cyclones (TCs) may be significantly increased in response to global warming, as noted by Free *et al*. (2004), who have written "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming," citing in support of this statement the studies of Emanuel (1987), Henderson-Sellers *et al*. (1998), and Knutson *et al*. (1998). Before accepting this climate-model-based projection, it is important to consider what drives tropical cyclone activity in the real world.

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) conclude "the effect of global warming on the number of tropical cyclones is presently unknown," and "there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe." They report there is "little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers."

In a second early analysis of the topic, Henderson-Sellers *et al*. (1998) determined "there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses," "global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill," and "the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy."

Walsh (2004) acknowledged "there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming." Nevertheless, Walsh suggested "there is likely to be some increase in maximum tropical cyclone intensities in a warmer world," "it is probable that this would be accompanied by increases in mean tropical cyclone intensities," and "these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%." He put the date of possible detection of these increases "sometime after 2050," little knowing two such claims would be made the very next year.

The historic contentions came from Emanuel (2005), who claimed to have found a hurricane power dissipation index had increased by approximately 50% for the Atlantic basin and the Northwest Pacific basin since the mid-1970s, and from Webster *et al*. (2005), who contended the number of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975–1989) and a more recent (1990–2004) 15-year period. In a challenge to both these claims, Klotzbach (2006) wrote "many questions have been raised regarding the data quality in the earlier part of their analysis periods," and he performed a new analysis based on a "near-homogeneous" global dataset for the period 1986–2005.

Klotzbach first tabulated global tropical cyclone (TC) activity using best track data, which he described as "the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers," for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian, and South Pacific). He then determined trends of worldwide TC frequency and intensity over the period 1986–2005, during which time global SSTs are purported to have risen by about 0.2–0.4°C. Klotzbach found "a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin," but also "a considerable decreasing trend for the Northeast Pacific." Combining these observations with the fact that "all other basins showed small trends," he concluded there had been "no significant change in global net tropical cyclone activity" over the past two decades.

With respect to Category 4 and 5 hurricanes, Klotzbach found there had been a "small increase" in their numbers from the first half of the study period (1986–1995) to the last half (1996–2005), but he noted "most of this increase is likely due to improved observational technology." Klotzbach declared his findings were "contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al*. (2005)," in that the global TC data did "not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years."

Landsea *et al*. (2006) asked whether "the global tropical cyclone databases [are] sufficiently reliable to ascertain long-term trends in tropical cyclone intensity, particularly in the frequency of extreme tropical cyclones (categories 4 and 5 on the Saffir-Simpson Hurricane Scale)." They analyzed the history of a number of operational changes at various tropical cyclone warning centers they theorized might have led to "more frequent identification of extreme tropical cyclones," as well as an unreal "shift to stronger maximum sustained surface wind," investigating in particular in this regard the Dorvak Technique for estimating tropical cyclone intensity.

The four researchers found "trend analyses for extreme tropical cyclones are unreliable because of operational changes that have artificially resulted in more intense tropical cyclones being recorded [with the passing of time], casting severe doubts on any such trend linkages to global warming." In addition, they note "data from the only two basins that have had regular aircraft reconnaissance—the Atlantic and Northwest Pacific—show that no significant trends exist in tropical cyclone activity when records back to at least 1960 are examined (Landsea, 2005; Chan, 2006)," while additionally noting "Klotzbach (2006) has shown that extreme tropical cyclones and overall tropical cyclone activity have globally been flat from 1986 until 2005, despite a sea surface temperature warming of 0.25°C."

Kossin *et al*. (2007) note "the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous," adding this "known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates." As an important first step in resolving this problem, Kossin *et al*. "constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates." They analyzed the resultant homogenized data for temporal trends over the period 1984–2004 for all major ocean basins and the global ocean as a whole.

The five scientists report, "using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic." Therefore, noting "the Atlantic basin accounts for less than 15% of global hurricane activity," they conclude "this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity." They concluded, "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future."

Vecchi and Soden (2007) used climate models and real-world observations "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They conclude "changes in local sea surface temperature are inadequate for characterizing even the sign of changes in potential intensity."

Reporting on the International Summit on Hurricanes and Climate Change held in May 2007 on the Greek island of Crete, where 77 academics and stakeholders from 18 countries participated in a free-ranging discussion of hurricanes and climate change, Elsner (2008) writes, "the question of whether we can ascribe a change in tropical cyclone intensity to anthropogenic climate change is still open." On the question of a warming-induced increase in hurricane frequency, he states the science was even more unsettled. Although "most models," in his words, indicate "an overall decrease in the number of storms," he notes not even all models agree on the change in individual basin tropical cyclone numbers, "with some models showing an increase in the Atlantic and others a decrease."

Further confusion was raised by Nolan and Rappin (2008), who extended the methodology of Nolan *et al*. (2007) to include a prescribed wind as a function of height that remains approximately constant during the genesis of tropical cyclones in environments of radiative-convective equilibrium partially defined by sea surface temperature (SST). They employed the modified methodology to explore what happens when SSTs rise. This approach revealed "increasing sea surface temperature does not allow TC genesis to overcome greater shear." In fact, they note "the opposite trend is found," and "the new and surprising result of this study is that the effect of shear in suppressing TC genesis actually increases as the SST of the radiative-convective equilibrium environment is increased."

This model-based finding was analogous to the observation-based result of Vecchi and Knutson (2008), who found as the SST of the main development region of North Atlantic TCs had increased over the past 125 years, certain aspects of climate changed in ways that may have made the North Atlantic "more favorable to cyclogenesis, while at the same time making the overall environment less favorable to TC maintenance." It is interesting that Nolan and Rappin conclude their paper with the intriguing question, "Do these results explain recent general circulation modeling studies predicting fewer tropical cyclones in a global warming world (e.g., Bengtsson *et al*. 2007)?"

Fan and Liu (2008) present a brief review and synthesis of the major research advances and findings of paleotempestology, which they describe as "a young science" that "studies past typhoon activity spanning several centuries to millennia before the instrumental era through the use of geological proxies and historical documentary records." They found "there does not exist a simple linear relationship between typhoon frequency and Holocene climate (temperature) change," especially of the type suggested by climate models. They report "on the contrary, typhoon frequency seemed to have increased at least regionally during the coldest phases of the Little Ice Age." They also note "more typhoons and hurricanes make landfalls in China, Central and North America during [cooler] La Niña years than [warmer] El Niño years." Consequently, and following their own advice about the need "to extend the time span of typhoon activity records" to help resolve the debate over the nature of climate change effects on this important weather phenomenon, Fan and Liu demonstrated the models likely have even the sign of the temperature effect on typhoon activity wrong, as global warming seems to reduce tropical cyclone activity over both the long term and the short term.

Chan (2009) studied five ocean basins—the Atlantic (1960–2007), Western North Pacific (1960–2007), Eastern North Pacific (1960–2007), South Indian Ocean (1981–2007), and South Pacific (1981–2007)—examining the relationship between the seasonally averaged maximum potential intensity (MPI, an index of thermodynamic forcing) over each basin and the frequency of occurrence of intense TCs within that basin. This work revealed "only in the Atlantic does the MPI have a statistically significant relationship with the number of intense TCs, explaining about 40% of the [observed] variance," whereas "in other ocean basins, there is either no correlation or the correlation is not significant." Even in the Atlantic, where a significant correlation exists between thermodynamic or temperature-related factors and the frequency of intense TCs, it is not clear whether global warming will produce a net increase in TC frequency, because model projections also suggest the increase in vertical wind shear associated with an increase in sea surface temperature tends to work against intense TC development. Therefore, Chan concludes, "it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario."

Wang and Lee (2009) note in the Western Hemisphere, tropical cyclones "can form and develop in both the tropical North Atlantic (NA) and eastern North Pacific (ENP) Oceans, which are separated by the narrow landmass of Central America," and "in comparison with TCs in the NA, TCs in the ENP have received less attention, although TC activity is generally greater in the ENP than in the NA (e.g., Maloney and Hartmann, 2000; Romero-Vadillo *et al*., 2007)." In exploring how the TC activities of the NA and ENP ocean basins might be related to each other over the periods 1949–2007 and 1979–2007, they employed several datasets to calculate the index of accumulated cyclone energy (ACE), which accounts for the number, strength, and duration of all TCs in a given season. They discovered "TC activity in the NA varies out-of-phase with that in the ENP on both interannual and multidecadal timescales," so "when TC activity in the NA increases (decreases), TC activity in the ENP decreases (increases)." In addition, they found "the out-of-phase relationship seems to [have] become stronger in the recent decades." The interannual and multidecadal correlations between the NA and ENP ACE indices were -0.70 and -0.43, respectively, for the period 1949–2007, but -0.79 and -0.59, respectively, for the period 1979–2007. In terms of the combined TC activity over the NA and ENP ocean basins as a whole, there is little variability on either interannual or multidecadal timescales. The real-world empirical data thus suggest the variability that does exist over the two basins has grown slightly weaker as Earth has warmed over the past six decades, running counter to claims that Earth's hurricanes or tropical cyclones should become more numerous, stronger, and longer-lasting as temperatures rise.

Wang *et al*. (2010) examined cross-basin spatial-temporal variations of TC storm days for the Western North Pacific (WNP), Eastern North Pacific (ENP), North Atlantic (NAT), North Indian Ocean (NIO), and Southern Hemisphere Ocean (SHO) over the period 1965–2008, for which period satellite data were obtained from the U.S. Navy's Joint Typhoon Warning Center for the WNP, NIO, and SHO, and from NASA's U.S. National Hurricane Center for the NAT and ENP. They report "over the period of 1965–2008, the global TC activity, as measured by storm days, shows a large amplitude fluctuation regulated by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, but has no trend, suggesting that the rising temperature so far has not yet [had] an impact on the global total number of storm days." This further implies "the spatial variation of SST, rather than the global mean temperature, may be more relevant to understanding the change of the global storm days."

Maue (2011) obtained global TC life cycle data from the IBTrACS database of Knapp *et al*. (2010), which contains six-hourly best-track positions and intensity estimates for the period 1970–2010, from which he calculated the accumulated cyclone energy (ACE) metric (Bell *et al*., 2000), which is analogous to the power dissipation index (PDI) used by Emanuel (2005) in his attempt to link hurricanes with global warming. Maue found "in the pentad since 2006, Northern Hemisphere and global tropical cyclone ACE has decreased dramatically to the lowest levels since the late 1970s." He also found "the global frequency of tropical cyclones has reached a historical low." He noted "a total of 69 TCs were counted during calendar year 2010, the fewest observed in the past 40 years with reliable frequency data." Over the four-decade period, "12-month running-sums of the number of global TCs of at least tropical storm force has averaged 87," and "the minimum number of 64 TCs was recently tallied through May 2011." Maue noted "there is no significant linear trend in the frequency of global TCs," in agreement with the analysis of Wang *et al*. (2010). "[T]his current period of record inactivity," as Maue describes it, suggests the long-held contention that global warming increases the frequency and intensity of tropical storms is simply not true.

Noting "Quaternary data have not figured prominently in recent debates concerning TC natural variability versus potential anthropogenic global warming-induced changes, nor have the Quaternary data been used to any substantial degree in numerical model projections concerning the future behavior of TCs," Nott (2011) provided a brief review of the subject, wring there are "at least 15 different methods for reconstructing long-term records of TCs."

The Australian researcher reports "recent analyses of corrected historical TC records suggest that there are no definitive trends towards an increase in the frequency of high-intensity TCs for the Atlantic Ocean region (Knutson *et al*., 2010), the northwest Pacific (Chan, 2006; Kossin *et al*., 2007) and the Australian region, South Pacific and south Indian oceans (Kuleshov *et al*., 2010)." He points out, "over multi-century to millennial timescales, substantial change has occurred in virtually all TC-generating regions of the globe," with "alternating periods of lesser and greater activity." He notes "the longer, coarser-resolution records display periods from multi-century to over a millennium in length, whereas the higher-resolution records register multi-decadal to centennial-length periodicities."

In some of these cases, Nott states, "different climate states, such as periods dominated by El Niños and La Niñas, appear to be responsible for the TC variability," whereas in other cases the responsible factor seems to be shifts in the position of the jet stream, solar variability, or some unknown cause. Nott notes "there is still considerably more data needed before causes of the long-term variability of TCs can be comprehensively identified" and "a better understanding of this long-term variability will be critical to understanding the likely future behavior of TCs globally and especially so when attempting to detect and attribute those future changes."

In a study designed to explore "the question of whether and to what extent global warming may be changing tropical cyclone activity," Grossmann and Morgan (2011) reviewed the scientific literature related to the possible effects on TC frequency and intensity of climate-model projected consequences of continued atmospheric greenhouse gas enrichment. They found "while Atlantic TCs have recently become more intense, evidence for changes in other basins is not persuasive, and changes in the Atlantic cannot be clearly attributed to either natural variability or climate change." They state "the presence of a possible climate change signal in TC activity is difficult to detect because inter-annual variability necessitates analysis over longer time periods than available data allow," and because "projections of future TC activity are hindered by computational limitations and uncertainties about changes in regional climate, large-scale patterns, and TC response."

While noting "scientific uncertainty about whether and how climate change will affect TCs in the future may not be resolved for decades," Grossmann and Morgan go on to suggest even if climate change "does not result in any significant increase in the intensity or frequency of future tropical cyclones" nor "lead to significant sea-level rise," human vulnerability in areas prone to land-falling hurricanes "will likely continue to increase significantly due to the continuing growth of populations and capital stock in high risk areas," citing Pielke *et al*. (2008). They conclude it would be wise "to induce greater protective action," and "there is a need to act now to reduce the existing high vulnerability to these storms," which will continue to constitute a real and present danger to people and infrastructure in coastal areas regardless of whether the frequency and degree of that danger increases or decreases.

Although many studies have explored the impacts of changes in sea surface temperature on various properties of tropical cyclones, the reverse phenomenon—the impacts of TCs on SSTs—has been less discussed. It has been known for decades, however, as reported by Dare and McBride (2011), that strong winds associated with TCs tend to reduce SSTs beneath such storms, as described by Fisher (1958), Leipper (1967), Brand (1971), Price (1981), Bender *et al*. (1993), Hart *et al*. (2007), Price *et al*. (2008), Jansen *et al*. (2010), and Hart (2011). This cold surface wake, as they describe it, "may extend for hundreds of kilometers adjacent to the storm track (Nelson, 1996; Emanuel, 2001)," and it can spread to larger scales over time, as reported by Sobel and Camargo (2005). As for the magnitude of the SST reduction within the TC wake, Dare and McBride write it can "range from less than 1°C (Cione *et al*., 2000), up to 3° (Shay *et al*., 1991), 4° (Price *et al*., 2008), 5° (Price, 1981), 6° (Berg, 2002), 7° (Walker *et al*., 2005), and 9°C (Lin *et al*., 2003)."

Using the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp *et al*., 2009) to provide the latitudes and longitudes at six-hour intervals for all TCs that occurred worldwide between September 1, 1981 and December, 31 2008, together with a corresponding set of SST data provided by NOAA's National Climatic Data Center at every 0.25° of latitude and longitude (Reynolds *et al*., 2007), Dare and McBride calculated the mean magnitude of the SST reductions and the average amount of time required for the reduced SSTs to return to pre-storm values. This effort revealed the time of maximum SST cooling occurred one day after cyclone passage, when the SST depression averaged 0.9°C. Thereafter, they report 44% of the SST depressions returned to normal within five days, while 88% of them recovered within 30 days. And although there were differences among individual cyclone basins, they say the individual basin results were in broad agreement with the global mean results. Finally, they report "cyclones occurring in the first half of the cyclone season disrupt the seasonal warming trend, which is not resumed until 20–30 days after cyclone passage," while "cyclone occurrences in the latter half of the season bring about a 0.5°C temperature drop from which the ocean does not recover due to the seasonal cooling cycle." Each TC occurring somewhere in the world leaves behind it a significantly altered SST environment that would be expected to have an effect 20 to 30 days later on other TCs that might pass through the same location.

Manucharyan *et al*. (2011) analyzed the effects of TCs on other TCs using several representative cases of time-dependent mixing that yielded the same annual mean values of vertical diffusivity, conforming with the studies of Jansen and Ferrari (2009) and Fedorov *et al*. (2010), wherein spatially uniform (but varying in time) mixing is imposed on zonal bands in the upper ocean. This work revealed "a weak surface cooling at the location of the mixing (~0.3°C), a strong warming of the equatorial cold tongue (~2°C), and a moderate warming in middle to high latitudes (0.5°C–1°C)," together with "a deepening of the tropical thermocline with subsurface temperature anomalies extending to 500 m [depth]." They state "additional mixing leads to an enhanced oceanic heat transport from the regions of increased mixing toward high latitudes and the equatorial region." But "ultimately," they continue, "simulations with TC-resolving climate models will be necessary to fully understand the role of tropical cyclones in climate," for they note "the current generation of GCMs [is] only slowly approaching this limit and [is] still unable to reproduce many characteristics of the observed hurricanes, especially of the strongest storms critical for the ocean mixing (e.g., Gualdi *et al*., 2008; Scoccimarro *et al*., 2011)."

Nott and Forsyth (2012) write, "understanding the long-term natural variability of tropical cyclones (TCs) is important for forecasting their future behavior and for the detection and attribution of changes in their activity as a consequence of anthropogenically induced climate change." They point out, "critical to these endeavors is determining whether, over the long-term, TCs occur randomly or display identifiable patterns influenced by one or several factors."

The two researchers present "new sedimentary data from the southwest (SW) Pacific and southeast (SE) Indian Ocean regions which allow us to make comparisons with existing sediment records from the Atlantic Ocean (Donnelly and Woodruff, 2007; Mann *et al*., 2009), northwest (NW) Pacific (Woodruff *et al*., 2009), Gulf of Mexico (Liu and Fearn, 1993, 2000; Lane *et al*., 2011) and the Gulf of Carpentaria, Australia (Rhodes *et al*., 1980)." They find "long-term global TC activity is not random." Instead, there is "a substantial degree of synchroneity in global intense TC behavior over the past 3,000 to 5,000 years." And they report "one of the most striking aspects of these records is they all display extended alternating periods (centuries to millennia) of relative quiescence and heightened intense TC activity irrespective of both the resolution and type of long-term TC record."

Something yet unknown has orchestrated the ebbing and flowing of global TC activity over the past 5,000 years. We do know it has not been changes in the atmosphere's CO_2 concentration, which has remained relatively stable over this entire period except for the past 100 years, when it has risen substantially without any demonstrable change in global TC activity. There is no compelling reason to believe further increase in the air's CO_2 content will have any significant impact on these destructive storms.

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Appendix 1

Acronyms

ACWT	Atlantic core water temperature
AGAGE	Advanced Global Atmospheric Gases Experiment
AGW	anthropogenic global warming
AMF	*arbuscular mycorrhizal* fungi
AMO	Atlantic Multidecadal Oscillation
AMSR	Advanced Microwave Scanning Radiometer
APSIM	Agricultural Production Systems Simulator
AO/NAO	Arctic Oscillation/North Atlantic Oscillation
AsA	ascorbic acid
ASI	aeolian sand influx
ATLAS	Airborne Thermal and Land Applications Sensor
AVHRR	Advanced Very High Resolution Radiometer
Ba	barium
BATS	Bermuda Atlantic Time-Series Study
BC2	Carlsbad Cavern (New Mexico)
BCC	Buckeye Creek Cave (West Virginia)
BioCON	Biodiversity, Carbon Dioxide, and Nitrogen Effects on Ecosystem Functioning
BIOME3	Biogeochemical Model
BP	before present
BSW	bog surface wetness
Bt	*Bacillus thuringiensis*
BYDV	barley yellow dwarf virus
Ca	calcium
CAM	Crassulacean Acid Metabolism
CASA	Carnegie-Ames-Stanford Approach
CBSC	Carbon-based secondary compounds
CCN	Cloud condensation nuclei
CDC	Canadian Drought Code
CERES	Clouds and the Earth's Radiant Energy System
CEVSA	Carbon Exchanges in the Vegetation-Soil-Atmosphere System
CFC	chlorofluorocarbons
CGCM	Coupled General Circulation Models
CH_2CII	iodocarbon chloroiodomethane
CH_3C_1	methyl chloride
CH_4	methane
CH_2I_2	diiodomethane
CHD	coronary heart disease
CMAP	Climate Prediction Center Merged Analysis of Precipitation
CO_2	carbon dioxide
CPR	Continuous Plankton Recorder
CPY	Climactic Pointer Years
CRII	cosmic ray-induced ionization
CRP1	Core Research Project 1
CRU	Climate Research Unit
CS_2	carbon disulfide
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CWP	Current Warm Period
CVD	cardiovascular disease
CZCS	Coastal Zone Color Scanner
DACP	Dark Ages cold period
DDG	dry distilled grain

DGGE	denaturing gradient gel electrophoresis
DM	dry matter
DMS	dimethyl sulfide
DOC	dissolved organic carbon
ECCO	Estimating Circulation and Climate of the Ocean
ECMWF	European Centre for Medium-Range Weather Forecasts
EDC96	European Project for Ice Coring in Antarctica Dome C
EIA	Energy Information Administration (U.S.)
EF-Tu	protein synthesis elongation factor
ENSO	El Nino-Southern Oscillation
EQC	eolian quartz content
FACE	Free-air CO_2 Enrichment
FACTS	Forest Atmosphere Carbon Transfer and Storage
FB	Foxe Basin
GBR	Great Barrier Reef
GCM	General Circulation Models
GCR	galactic cosmic rays
GCTE	Global Change and Terrestrial Ecosystems
GDP	Gross Domestic Product
GEI	Glacier Expansion Index
GHG	green house gas(es)
GIMMS	Global Inventory Modeling and Mapping Studies
GIS	Greenland Ice Sheet
GISS	Goddard Institute of Space Studies
GLO-PEM	Global Production Efficiency Model
gNDVI	Normalized Difference Vegetation Index over the Growing Season
GPCP	Global Precipitation Climatology Project
gr	gram(s)
GRACE	Gravity Recovery and Climate Experiment
GREET	Greenhouse gases Regulated Emissions and Energy Use in Transportation
GSH	glutathione
GSL	global sea level
HC1	Hidden Cave (Guadalupe Mountains)
HR	heterotrophic respiration
HSG	hematite stained grain
IE	infection efficiency
IMAR	Inner Mongolia Autonomous Region
IMR	Indian Monsoon rainfall
IPCC	Intergovernmental Panel on Climate Change
IPCC 2007-I	Intergovernmental Panel on Climate Change -- Group 1 Contribution
IPCC 2007-II	Intergovernmental Panel on Climate Change -- Group II Contribution
IPCC 2007-II	Intergovernmental Panel on Climate Change -- Group III Contribution
IPCC-FAR	Intergovernmental Panel on Climate Change -- First Assessment Report
IPCC-SAR	Intergovernmental Panel on Climate Change -- Second Assessment Report
IPCC-TAR	Intergovernmental Panel on Climate Change -- Third Assessment Report
IPCC-AR4	Intergovernmental Panel on Climate Change -- Fourth Assessment Report
IPCC-AR5	Intergovernmental Panel on Climate Change -- Fifth Assessment Report
IRD	ice rafted debris
ISCCP	International Satellite Cloud Climatology Project
ISM	Indian Summer Monsoon
ITCZ	Intertropical Convergence Zone
ITS2	Internal Transcribed Spacer Region 2
IUCN	International Union for Conservation of Nature
LBM	larch budmoth
LCA	low cloud amount
LCLU	land cover and land use
LGM	Last Glacial Maximum
LIA	Little Ice Age
LST	land surface temperature
LTM	long-term mean standardization
m	meter
Ma BP	million years before present
MAAT	mean annual air temperature

MBP	mass balance potential
MDR	main development region
ME	surface melt
MJ	mega joule
MS	methanesulfonate
MSA	methanesulfonic Acid
MTBE	methyl tertiary butyl ether
MWP	Medieval Warm Period
MXD	maximum latewood density
MY	multiyear
N_2O	nitrous oxide
NABE	North Atlantic Bloom Experiment
NADW	North Atlantic deep water
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NAS	National Academy of Sciences
NDVI	Normalized Difference Vegetation Index
NEP	net ecosystem production
NIPCC	Nongovernmental International Panel on Climate Change
NMHC	non-methane hydrocarbon
NPP	net primary production
nss-SO_4^{2-}	non-sea-salt sulfate
NWS	National Weather Service
O_3	ozone
OCS	carbonyl sulfide
OLR	outgoing longwave radiation
OM	organic matter
OTC	open-top chambers
P	precipitation
PAL	Pathfinder AVHRR [Advanced Very High Resolution Radiometer] Land
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PF	polar front
PGR	post-glacial rebound
PI	potential intensity
PIZ	perennial ice zone
ppb	parts per billion
ppm	parts per million
Ps	solid precipitation
RACM	Regional Atmospheric Climate Model
RCC	rapid climate change
RCS	regional curve standardization
Rd	ratio of diffuse
Rda	area-based dark respiration
Rdm	mass-based dark respiration
rDNA	ribosomal deoxyribonucleic acid
Rg	solar irradiance
ROS	reactive oxygen species
RWP	Roman Warm Period
SACC	Screen-Aided CO_2 Control
SAT	surface air temperature
SB	Southern Beaufort Sea
SCC	Swiss Canopy Crane Project
SCPDSI	Self-Calibrating Palmer Drought Severity Index
SeaWiFS	Sea-Viewing Wide Field-Of-View Sensor
SEPP	Science & Environmental Policy Project
SFP	South Fork Payette
SMB	surface mass balance
SMR	snowmelt runoff
SODA	Simple Ocean Data Assimilation
SOM	soil organic matter
SPAR	Soil-Plant-Atmosphere-Research Facility (Mississippi)
SPCZ	South Pacific Convergence Zone
SPM	Summaries for Policymakers
SPS	sucrose-phosphate synthase
SSM/I	Special Sensor Microwave Imager
SSMR	Scanning Multichannel Microwave Radiometer
SN/SSN	sunspot number
SST	sea surface temperatures
STF	subtropical front
SU	surface sublimation
SWE	snow water equivalent
SWF	shortwave flux

SWM	Southwest Monsoon
TBE	tick-borne encephalitis
TBEV	tick-borne encephalitis virus
TC	tropical cyclones
Tmax	maximum temperature
Tmin	minimum temperature
TMI	Tropical Rainfall Measuring Mission Microwave Imager
T_{opt}	optimum temperature
TP	Tibetan Plateau
TRFO	tropical rainforest
TRMM	Tropical Rainfall Measuring Mission
TSI	total solar irradiance
UHI	urban heat island
UNEP	United Nations Environment Program
UV	ultraviolet
VS	vertical wind shear
WAIS	West Antarctic Ice Sheet
WH	Western Hudson Bay
WMO	World Meteorological Organization
WNP	Western North Pacific
WSC	water-soluble carbohydrate
WT	wild type
WUE	water use efficiency

Appendix 2

Authors, Contributors, and Reviewers

Lead Authors/Editors

Idso, Craig D.
Center for the Study of Carbon Dioxide and Global Change
USA

Carter, Robert M.
Emeritus Fellow
Institute of Public Affairs
Australia

Singer, S. Fred
Science and Environmental Policy Project
USA

Chapter Lead Authors

Ball, Timothy
Research Fellow
Frontier Centre for Public Policy
Canada

Carter, Robert M.
Emeritus Fellow
Institute of Public Affairs
Australia

Easterbrook, Don J.
Professor Emeritus of Geology
Western Washington University
USA

Idso, Craig D.
Center for the Study of Carbon Dioxide and Global Change
USA

Idso, Sherwood
Center for the Study of Carbon Dioxide and Global Change
USA

Khandekar, Madhav
Former Research Scientist
Environment Canada
Canada

Kininmonth, William
Science Advisor
Australian Climate Science Coalition
Australia

de Lange, Willem
Science and Engineering Department
The University of Waikato
New Zealand

Lüning, Sebastian
Geologist and Author
Germany

Lupo, Anthony
School of Natural Resources
University of Missouri
USA

Ollier, Cliff
School of Earth and Geographical Sciences
University of Western Australia
Australia

Soon, Willie
Independent Scientist
USA

Contributing Authors

Armstrong, J. Scott
Wharton School
University of Pennsylvania
USA

D'Aleo, Joseph
Co-chief Meteorologist
Weatherbell Analytic
USA

Easterbrook, Don J.
Professor Emeritus of Geology
Western Washington University
USA

Green, Kesten
International Graduate School of Business
University of South Australia
Australia

McKitrick, Ross
Department of Economics
University of Guelph
Canada

Ollier, Cliff
School of Earth and Geographical Sciences
University of Western Australia
Australia

Segalstad, Tom
Resource and Environmental Geology
University of Oslo
Norway

Singer, S. Fred
Science and Environmental Policy Project
USA

Spencer, Roy
Principal Research Scientist
University of Alabama in Huntsville
USA

Chapter Reviewers

Abdussamatov, Habibullo
Space Research Laboratory
Pulkovo Observatory
Russian Academy of Sciences
Russia

Bastardi, Joe
Co-chief Meteorologist
Weatherbell Analytic
USA

Battaglia, Franco
Professor of Environmental Chemistry
University of Modena
Italy

Bowen, David Q.
Professor Emeritus, School of Earth & Ocean Sciences
Cardiff University
UK

Clark, Roy
Ventura Photonics
USA

Courtillot, Vincent
Professor Emeritus
University Paris Diderot and
Institut de Physique du Globe
France

Essex, Christopher
Department of Applied Mathematics
University of Western Ontario
Canada

Evans, David
Independent Scientist, Sciencespeak.com, and Former
Carbon Modeller
Australian Greenhouse Office
Australia

Floderus, Sören
Consultant
SF Bureau
Denmark

Franks, Stewart W.
School of Engineering
University of Newcastle
Australia

Friis-Christensen, Eigil
Professor Emeritus
National Space Institute
Technical University of Denmark
Denmark

Goldberg, Fred
Swedish Polar Institute
Sweden

Gould, Laurence
Professor of Physics
University of Hartford
USA

Gray, William
Emeritus Professor of Atmospheric Science
Colorado State University
USA

Gray, Vincent Richard
Climate Consultant
New Zealand

Hayden, Howard
Professor of Physics Emeritus
University of Connecticut
USA

Hovland, Martin
Professor Emeritus
Centre for Geobiology
University of Bergen
Norway

Kärner, Olavi
Atmospheric Sensing Group
Tartu Observatory
Estonia

O'Brien, James
Department of Earth, Ocean, and Atmospheric Science
Florida State University
USA

Paltridge, Garth
Emeritus Professor and Honorary Research Fellow
University of Tasmania
Australia

Rapp, Donald
Senior Research Scientist and Division Chief Technologist (retired)
Jet Propulsion Lab
USA

Ribbing, Carl
Department of Engineering Sciences, Solid State Physics
Uppsala University
Sweden

Scafetta, Nicola
Department of Physics
Duke University
USA

Shade, John
Industrial Statistics Consultant
UK

Sharp, Gary
Independent Consultant
Center for Climate/
Ocean Resources Study
USA

Solheim, Jan-Erik
Professor emeritus
Department of Physics and Technology
University of Tromsø
Norway

Uriarte Cantolla, Antón
Sociedad de Ciencias Naturales Aranzadi
Spain

Weber, Gerd-Rainer
Independent Meteorologist
Germany

Editors

Karnick , S.T.
The Heartland Institute
USA

Bast, Diane Carol
The Heartland Institute
USA