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Thin Solid Films
Volume 517, Issue 11, 2 April

Sulfur dioxide initiates global climate change in four ways

Abstract

Global climate change, prior to the 20th century, appears to have been initiated primarily by major changes in volcanic activity. Sulfur dioxide (SO2) is the most voluminous chemically active gas emitted by volcanoes and is readily oxidized to sulfuric acid normally within weeks.
But trace amounts of SO2 exert significant influence on climate.
All major historic volcanic eruptions have formed sulfuric acid aerosols in the lower stratosphere that cooled the earth's surface -0.5 °C for typically three years.
While such events are currently happening once every 80years, there are times in geologic history when they occurred every few to a dozen years.
These were times when the earth was cooled incrementally into major ice ages.
There have also been two dozen times during the past 46,000years when major volcanic eruptions occurred every year or two or even several times per year for decades.
Each of these times was contemporaneous with very rapid global warming.
Large volumes of SO2 erupted frequently appear to overdrive the oxidizing capacity of the atmosphere resulting in very rapid warming.
Such warming and associated acid rain becomes extreme when millions of cubic kilometers of basalt are erupted in much less than one million years.
These are the times of the greatest mass extinctions.
When major volcanic eruptions do not occur for decades to hundreds of years, the atmosphere can oxidize all pollutants, leading to a very thin atmosphere, global cooling and decadal drought. Prior to the 20th century, increases in atmospheric carbon dioxide (CO2) followed increases in temperature initiated by changes in SO2.
By 1962, man burning fossil fuels was adding SO2 to the atmosphere at a rate equivalent to one "large" volcanic eruption each 1.7years.
Global temperatures increased slowly from 1890 to 1950 as anthropogenic sulfur increased slowly.
Global temperatures increased more rapidly after 1950 as the rate of anthropogenic sulfur emissions increased.
By 1980 anthropogenic sulfur emissions peaked and began to decrease because of major efforts especially in Japan, Europe, and the United States to reduce acid rain.
Atmospheric concentrations of methane began decreasing in 1990 and have remained nearly constant since 2000, demonstrating an increase in oxidizing capacity.
Global temperatures became roughly constant around 2000 and even decreased beginning in late 2007.
Meanwhile atmospheric concentrations of carbon dioxide have continued to increase at the same rate that they have increased since 1970.
Thus SO2 is playing a far more active role in initiating and controlling global warming than recognized by the Intergovernmental Panel on Climate Change.
Massive reduction of SO2 should be a top priority in order to reduce both global warming and acid rain.
But man is also adding two to three orders of magnitude more CO2 per year to the climate than one "large" volcanic eruption added in the past.
Thus CO2, a greenhouse gas, is contributing to global warming and should be reduced. We have already significantly reduced SO2 emissions in order to reduce acid rain.
We know how to do it both technically and politically.

In the past, sudden climate change was typically triggered by sudden increases in volcanic activity.
Slow increases in greenhouse gases, therefore, do not appear as likely as currently thought to trigger tipping points where the climate suddenly changes.
However we do need to start planning an appropriate human response to future major increases in volcanic activity.

Introduction

The atmosphere is a very thin blanket of gases, aerosols, and minute particles that makes the earth habitable.
Over 90% of the atmosphere by mass is within 16km of the earth's surface [l]. Without an atmosphere, world temperatures would approach -19°C (-2°F) [2] but with the atmosphere the average world temperature has been within 0.7°C of 14°C (57.2°F) since 1880[3].
A small difference of 0.1 °C between the mean temperatures of the Medieval Warming Period and the Little Ice Age [4] had a major effect on climate change, glacial length, food supplies, and population growth [5], [6].
The atmosphere selectively reflects, refracts, scatters, absorbs, or transmits broadband radiant energy from the sun, infrared energy radiated outwards by the earth, and cosmic rays bombarding the earth from all directions.
Gases, aerosols, and particles in the atmosphere maintain a delicate and very dynamic balance such that the energy at the top of the atmosphere received from the sun equals the energy reflected or radiated by the earth and its atmosphere [7].
We will see below that very small changes in atmospheric chemistry can lead to major changes in reflection, refraction, scattering, absorption, and transmission that change global climate.
An analogy would be a horizontal slat window shade (venetian blind) where the very small amount of energy needed to rotate the slats could have a major effect on the solar energy reflected and transmitted.
The atmosphere originally formed from outgassing of the earth, primarily through volcanoes.
The atmosphere changed from reducing to oxidizing around 2.5Ga (billion years ago) when volcanism shifted from being primarily submarine to having a major subaerial component [8].
The major source of new gases in the atmosphere has been from volcanoes.
Volcanic gases are modified, for example, by chemical processes in the atmosphere, by plants converting carbon dioxide (CO2) to oxygen (02), by animals doing the reverse, by decay of animal and vegetable matter, by forest fires, and by chemical weathering of geologic materials.
The single most important chemical process in the atmosphere today is oxidation.
The atmosphere cleans itself of impurities by oxidizing them to form larger molecules that settle out or are rained out.
Similarly, the only well-known sources of regular major changes in atmospheric chemistry throughout geologic time are volcanoes, major fires and now human burning of fossil fuels.
Large volcanic eruptions that spew hundreds of megatons of water and gases occur today approximately once every 80years, but have been known in the past to occur as often as several times each year. Large meteoroids, the methane "clathrate gun hypothesis" [9], sudden draining of glacial lakes [10], massive iceberg discharges [11], and other possible climate changing events are orders of magnitude less common.

This paper explains the evidence for each of the four cardinal rates of SO2 erupted by volcanoes and their effects on global climate change (summarized in Table I).
The IPCC only discussed the moderate rate (II).
The other three rates are quite unexpected in the prevalent climatological thinking of today
For those who understand the widespread distribution of volcanoes, their sometimes extremely high rates of eruption, and the large volume of water and gases erupted, what is unexpected is why it has taken so long to recognize their important role in climate change.
SO2 is also emitted when fossil fuels are burned.
This paper provides the clearest link yet published between human activities and global climate change.
Similar delays were observed at the end of the last three glacial periods at 19ka, 125 ka and 240ka [14], [15], [16], [17]. CO2 is soluble in water and more soluble in cold water. Ocean temperature is therefore the primary natural control for atmospheric CO2 concentration [18].
Similarly, before the widespread growth of plants (-350Ma, million years ago), the mass of atmospheric CO2 may have been as large as 17 times the mass of pre-human atmospheric CO2 but global temperatures were not significantly higher [19]. In fact, glaciers were common.
These extremely important observations must be explored in detail before we can assess how much the 7.8Gt of carbon added to the atmosphere yearly by humans burning fossil fuel and manufacturing cement [20] is influencing global warming.
Volcanoes erupt large amounts of sulfur (Fig. I) and the most chemically active gas erupted by volcanoes in significant volumes is sulfur dioxide (SO2) [21], which is readily oxidized to sulfuric acid. Sulfuric acid, "because of its low vapor pressure, quickly attaches to aerosol particles" [22].
The **Intergovernmental Panel on Climate Change (IPCC) Working Group I** published an extensive report in 2007 [12] that concludes that carbon dioxide (CO2) is the most important cause of climate change and that the only important effect of volcanoes on climate change is to cause global cooling for a few years following large volcanic eruptions.
While the concentration of CO2 clearly has changed in phase with changes in global temperature in the past, recent data suggest that these changes actually followed changes in temperature. For example, Stott et al.
[13] observed that at the end of the last ice age, deep-sea temperatures warmed by -2°C between 19ka (thousand years ago) and 17 ka, preceding the rise in atmospheric CO2 and tropical sea-surface warming by -1000years. concludes that carbon dioxide (CO2) is the most important cause of climate change and that the only important effect of volcanoes on climate change is to cause global cooling for a few years following large volcanic eruptions.
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[13] observed that at the end of the last ice age, deep-sea temperatures warmed by -2°C between 19ka (thousand years ago) and 17 ka, preceding the rise in atmospheric CO2 and tropical sea-surface warming by -1000years.
There are numerous ideas about what initiates climate change.
Many of these processes may be at work, but in this paper, I propose that the concentration of SO2 has been the primary initiator of climate change prior to the industrial revolution beginning in 1850. The climate appears to have maintained a delicate balance among the four cardinal rates of SO2.
This is good news, because we have already developed effective technological and political ways to reduce SO2 emissions in order to reduce acid rain.
Throughout geologic history, changes in CO2 have been the result of climate change.
The prodigious emission of greenhouse gases by man may now have become a secondary initiator of climate change.

Section snippets

Moderate rate: Occasional large volcanic eruptions, short-term global cooling
The largest volcanic eruption in the past 95years was from Mt. Pinatubo in the Philippines in 1991 [24].
Pinatubo erupted into the atmosphere 491 to 921 Mt (megatons) of water (H20), 42 to 234Mt CO2, 15 to 19Mt SO2, and 3 to 16Mt chlorine (Cl) [25].
This eruption increased the total mass of the atmosphere [26], primarily with water, by only 0.23 ppm (parts per million).
The amount of SO2 added to the atmosphere was only 3.3 ppb (parts per billion), although the changes were much greater...

Volcanism and glacial epochs

Table SI (see Supplementary data) provides the most complete list available of all known large volcanic eruptions through the last 542million years.
These events typically have a Volcano Explosivity Index (VEI) [24], [57] of 6 or greater.
The red line in Fig. 2 shows the cumulative number of the largest known volcanic eruptions in the past 120m.y. (million years) based on the red highlighted entries in Table SI.
The general shape of this curve is what is most important and is probably a...
The oxidizing capacity of the atmosphere is limited
The primary oxidants in the atmosphere are ozone, the hydroxyl radical (OH) and hydrogen peroxide (H202) [23]. OH has been called the "tropospheric vacuum cleaner" [99] because it reacts with dozens of gases. In fact OH is responsible for removing -2380Mt of carbon monoxide (CO), -90Mt of SO2, and -1180Mt of other trace gases from the atmosphere each year [22].
Ozone in the stratosphere forms from the effects of ultraviolet sunlight on oxygen. OH and H202 form from ozone by photodissociation ...
This is exactly the time of greatest global warming coming out of the last ice age (green line). Fig. 5 shows this relationship in more detail. The purple line shows the GISP2 6180 proxy for temperature and ice volume for the past 25,000years [91].
The world was coldest during the Last Glacial Maximum (LGM) between 22 and 24ka, depending on...

High rate: Frequent large volcanic eruptions, global warming

Volcanic sulfate anomalies in the Greenland ice layers are significantly larger and more frequent between 15 and 7 ka as shown by the red bars in Fig. 4.**Anthropogenic warming**

The red bars in Fig. 10 show sulfate anomalies in the GISP2 ice core in Greenland from 1850 to 1985 [96] along with the names of known volcanic eruptions with their VEI [24].
The blue line shows mean yearly global surface temperature [131], [132].
The black line shows the amount of sulfur emitted by humans burning fossil fuel [133], [134]. During the 19th century, 72% of the ice layers had no volcanic sulfate. Since 1927, all layers had sulfate and the amount of sulfate increases proportionally ...
Extreme rate: Very frequent basaltic eruptions, mass extinctions
The largest known basaltic fissure eruption in the past 1000years is Laki in southern Iceland, which produced 14.7 km3 of basalt in 8months beginning in June, 1783 [48].
The 10 eruption episodes were not all that spectacular (VEI=4), with ash reaching altitudes of only 13km, but this 27-kmlong fissure complex emitted 122Mt of SO_2, more than 5 times that of Pinatubo, as well as 235Mt of H20, 15Mt of chlorine, 7Mt of fluorine, some hydrogen sulfide and some ammonia. Most of these gases...
Low rate: No volcanic eruptions, clean atmosphere, cooling and drought
The fourth type of abrupt climate change is very rapid cooling with widespread drought that appears to happen when the rate of volcanic activity decreases from a very high level to a very low level. The clearest example is known as the 8.2ka event (Fig. 5, Fig. 7) (Cardinal Rate I, Table I).
At approximately 8175years BP (Before Present) the temperature in Greenland dropped at least 3.3°C in less than 20years [192]. After 60 cold years, the temperature recovered in approximately 70years of drought

Discussion
The international debate over climate change has been between those who argue that periods of sudden warming have happened without man many times in the geologic past and those who argue that the prodigious amounts of gases emitted by man are causing the current warming. I have shown in this paper that both groups have merit and the mechanisms are similar. Sudden global warming has occurred dozens of times in the past 46,000years and each of those times is contemporaneous with a significantly...

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...Another side is that sulfur oxides emissions resulted from the burning of fossil fuels are primarily originated from humans' economic activities.

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According to the Ward (2009)'S study, at present, anthropogenic activities are releasing as much sulfur oxides every 1.7 years quantitated in Greenland as one "great" volcanic eruption.
Especially with the acceleration of regional economic and social development, for many emerging countries like China and India, global demand for energy will rise further as these countries' industrialization and urbanization move ahead, which led to a large number of sulfur oxides such as gaseous pollutants or granular pollutants emitted to the atmosphere, and thus had the tremendous harm to the regional ecological environment
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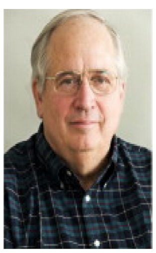

Peter L. Ward was educated at Noble & Greenough School (1961), Dartmouth College (BA in Geophysics, 1965) and Columbia University (Ph.D. in Seismology, 1970).
He began working on active volcanoes in 1963 in Alaska. His Ph. D. thesis was on a new interpretation of the geology of Iceland based on studies of small earthquakes and on
the relationship of these earthquakes to volcanoes and geothermal power sources.
He worked 27 years with the United States Geological Su rvey on volcanoes, earthquakes, and plate tectonics.
In the early 1970S he developed a prototype global volcano surveillance system using the ERTS satellite to collect data from ground instruments on volcanoes throughout the western U.S., Central America, and Iceland. In 1975, he became chief of the Branch of Seismology, a group of 140 scientists and staff.
He helped sell to Congress, develop and guide the new U. S. National Earthquake Hazards Reduction Program in 1977-1978. In 1990, he wrote and produced a 24-page magazine about living safely with earthquakes. Editions in English, Spanish, Chinese and Braille were distributed primarily in 41 Sunday-morning newspapers throughout Northern California to 3.3 million people, winning him two national awards.
His major publications in the 1990S explored the relationship between volcanoes and other geologic features of western North America with the motion of plates in the northeastern Pacific Ocean.
This led to significant new ideas about the origins and nature of volcanoes, granites, silicic volcanic provinces, flood basalts, and volcanic hot spots. He currently lives in Jackson, Wyoming, continuing his research on the effects of volcanoes on man. See www.tetontectonics.org 7'. (Photo by Irene Mellion).

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