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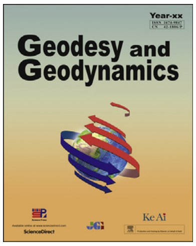

# A possible interrelation between Earth rotation and climatic variability at decadal time-scale

*Leonid Zotov*[a,b,*], *C. Bizouard*[c], *C.K. Shum*[d,e]

[a] *National Research University Higher School of Economics, Moscow Institute of Electronics and Mathematics, Moscow, Russia*
[b] *Lomonosov Moscow State University, Sternberg Astronomical Institute, Moscow, Russia*
[c] *SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universites, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*
[d] *Division of Geodetic Science, School of Earth Sciences, The Ohio State University, USA*
[e] *State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy & Geophysics, Chinese Academy of Sciences, Wuhan, China*

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ABSTRACT

Using multichannel singular spectrum analysis (MSSA) we decomposed climatic time series into principal components, and compared them with Earth rotation parameters. The global warming trends were initially subtracted. Similar quasi 60 and 20 year periodic oscillations have been found in the global mean Earth temperature anomaly (HadCRUT4) and global mean sea level (GMSL). Similar cycles were also found in Earth rotation variation. Over the last 160 years multi-decadal change of Earth's rotation velocity is correlated with the 60-year temperature anomaly, and Chandler wobble envelope reproduces the form of the 60-year oscillation noticed in GMSL. The quasi 20-year oscillation observed in GMSL is correlated with the Chandler wobble excitation. So, we assume that Earth's rotation and climate indexes are connected. Despite of all the clues hinting this connection, no sound conclusion can be done as far as ocean circulation modelling is not able to correctly catch angular momentum of the oscillatory modes.

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[*] *Corresponding author.* National Research University Higher School of Economics, Moscow Institute of Electronics and Mathematics, Tallinskaya ul. 34, Moscow, Russia.
E-mail address: wolftempus@gmail.com (L. Zotov).

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## 1. Introduction

In the last decades the International Panel on Climate Changes (IPCC) has published several reports, concerning climate variability [1]. Many observations have been presented and analysed, including Earth's temperature and global sea level (SL) changes, glacial melting, increase in concentration of greenhouse gases. Global warming trends are clearly seen in these data (Fig. 1) and their prediction using complex models of ocean and atmosphere dynamics is a major matter of IPCC concern. While these models include many factors, they still badly reproduce the so-called "natural variability", mostly composed of quasi 60- and 20-year variations of temperature (up to 0.3 °C) and SL (up to 30 mm) during the last 160 years. Such variations (Fig. 1) are evidenced by the data representing the global Earth's temperature anomaly (HadCRUT4) and the global mean sea level (GMSL) [2,3], sea surface temperature (HadSST) [4–9], and are shown in Fig. 2 after trends have been removed. The interpretation of these periodicities is not well understood. For example, 70-year temperature variations are usually related to the Atlantic Multi-decadal Oscillation (AMO) propagating in the northern Atlantic, influencing the continents of the Northern Hemisphere [4], and teleconnected with the Pacific Decadal (PDO) and Arctic (AO) oscillations. The quasi 20-year variability is inherent in the Indian and Pacific oceans [8]. These variations are often related to natural oscillatory modes of atmosphere, such as El Nino Southern Oscillation (ENSO) (composed of a few quasi-periodicities lying between 2 and 8 years) and North Atlantic Oscillation (NAO). The aim of this paper is to reassess such a link and deepen its meaning, by paying attention, at the same time, to the similarities between the climatic processes and Earth rotation changes, already noticed in references [10–12].

## 2. The quasi 20 year and 60 year climatic cycles

The above mentioned time series are decomposed by multichannel singular spectrum analysis (MSSA), for it allows to extract their periodic components with changing amplitudes, and their trend, as well as to suppress the noise.

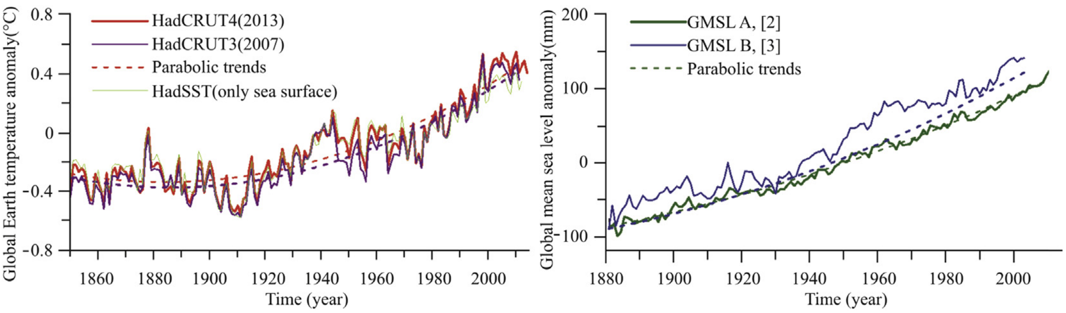

**Fig. 1 – Global Earth mean temperature (HadCRUT) (left) and global mean sea level (GMSL) (right) reconstructions A [2] and B [3].**

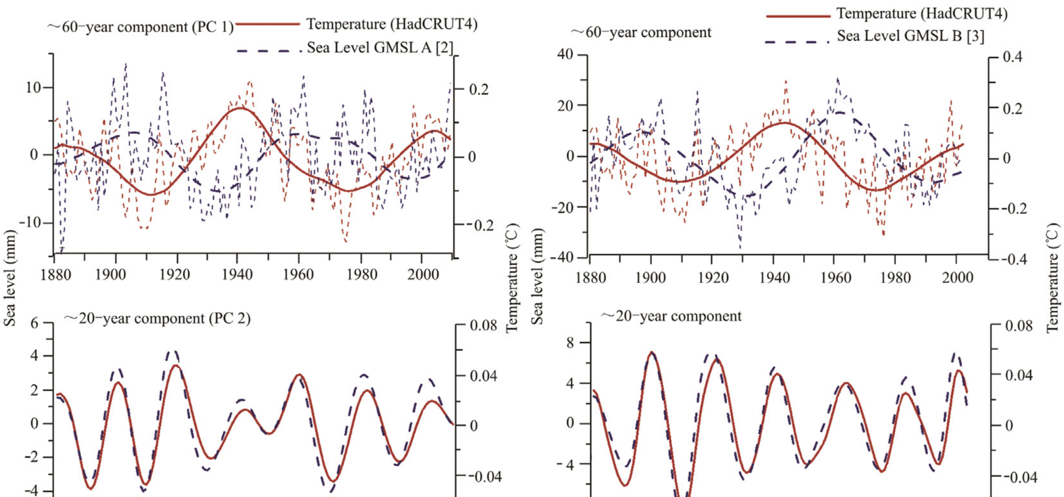

**Fig. 2 – 60-year PC 1 (top) and 20-year PC 2 (bottom) oscillations in the global Earth's temperature (solid red) and sea level (dash blue), extracted from HadCRUT4 and GMSL A (left) and from HadCRUT4 and GMSL B (right) using MSSA.**

This technique is an extension of empirical orthogonal functions (EOF) decomposition for multidimensional time series. As it is described in details in references [13–15] and adopted in our previous works [10,11,16], we just mention here that it is based on the singular valued decomposition (SVD) of the trajectory matrix, obtained by means of time series embedding into the $L$-dimensional space. The lag $L$ is the main parameter of the algorithm, and several heuristic strategies are recommended in the literature for its selection [15]. The principal components (PCs) of the time series can be reconstructed from the sequence of singular numbers (SNs) and corresponding eigenvectors. MSSA allows to extract correlated behaviour in the time series components. The first kind of input data is the global Earth's temperature (land + ocean) time series HadCRUT4 from the Hadley Centre (http://www.cru.uea.ac.uk/cru/data/temperature/) since 1850. The global temperature embeds both the sea surface temperature (HadSST) and the land surface temperature. The sea surface contribution is by far the most important (Fig. 1). Monthly values were smoothed and resampled at annual interval. The second kind of input data is the global mean sea level with two reconstructions: first one was made by Church & White [2] in CSIRO for the period 1880–2009 and abbreviated here as GMSL A, and the second one GMSL B was produced by Jevrejeva et al. [3] for the period 1700–2002 (used since 1880) with an annual resolution. For each time series the trend was modelled as second order (parabolic) polynomial (Table 1, Fig. 1), fitted by least squares method (LSM) and removed. The chosen model for the trend does not affect the essence of our results. While this trend is the most important parameter for the global warming community, we shall focus on natural variations. We incorporated the temperature and the sea level data into two-dimensional time series. They were processed by MSSA, selecting lag parameter $L = 22$ years. Separate 2–D processing for HadCRUT4/GMSL A and HadCRUT4/GMSL B time series was performed. The time series were normalized before restored during processing. In both cases quasi 60- and 20-year oscillations were found. They are presented in Fig. 2. Results for GMSL B (right) show larger amplitudes than those of GMSL A (left). We also found quasi 10-year oscillations, but their amplitudes (0.03 °C, 3 mm) has the order of the noise level, thus they are not presented [10,11]. Mean period, amplitude, and phase of these oscillations are determined by non-linear least squares method (NL LSM), applied to each time series separately. The results are presented in Table 2.

**Table 1 – Parameters of the parabolic trends subtracted and trend changes according to the model $a_0(t - t_0)^2 + a_1(t - t_0) + a_2$, where $t_0$=1880 yr.**

| | HadCRUT4 | GMSL A | GMSL B |
|---|---|---|---|
| $a_0$ | $4.882 \cdot 10^{-5}$ | 0.005 | 0.066 |
| $a_1$ | $36.758 \cdot 10^{-5}$ | 0.892 | 0.923 |
| $a_2$ | −0.336 °C | −154.904 mm | −66.771 mm |
| Rise for 1900–2000 | 0.647 °C | 158.75 mm | 184.73 mm |

## 3. Oceanic-atmospheric dynamics underlying multi-decadal cycles

As evidenced by Fig. 2, the 60 and 20-year oscillations exist in both temperature and sea level data. The 60-year SL component (PC 1) is delayed by about 20–30 years. Sea level rate (derivative) agrees in phase with the temperature changes much better. It can be explained by the delayed response of SL to the ocean surface temperature changes according to the differential equation

$$\frac{dSL(t)}{dt} = a(T(t) - T_0) \tag{1}$$

proposed in reference [7]. Here $SL(t)$ is sea level, $T(t)$ represents global surface Earth's temperature changes, $T_0$ is initial temperature value, $a$ is a prefactor coefficient. Such an equation corresponds to the low-frequency filter. The ocean, whose heat capacity is three orders of magnitudes larger than those of atmosphere, should have a delayed response to the air temperature changes.

However, the 20-year component of the sea level is not shifted with respect to the corresponding air surface temperature anomaly, as shown by Fig. 2, bottom. Thus, equation (1) is not suitable for 20 year oscillation. A feedback can be introduced into equation (1) (as in equation (2)), nevertheless, it does not resolve the issue.

MSSA can help to detect input and output of the dynamical system and identify its structure, because PCs have narrow spectral band and are often very close to the eigen functions of the system. Yet the dynamics of ocean and atmosphere interaction can reverse, depending on the time scale. On time intervals much longer than 20 years the sea level, related to the ocean heat content, should be rather consider as the system input, instead of the delayed response to the air surface temperature, which becomes the output. In other words, the ocean can rule the climate on multi-decadal and secular time intervals. Giving weight to this conjecture is the study of [17], showing that the level of Atlantic Ocean rises during the decay of the positive phase of Atlantic Multi-decadal Oscillation. For deepening this investigation, we have to introduce the North Atlantic Oscillation (NAO) index, representing the pressure difference between Azores high and Island low (it can be downloaded from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based, as recommended in reference [17]). Indeed, in references [17–19] it was

**Table 2 – Parameters of two major harmonics, obtained by NL LSM.**

| | HadCRUT4 (°C) | | GMSL A (mm) | | GMSL B (mm) | |
|---|---|---|---|---|---|---|
| Period, yr | 65.0 | 21.3 | 55.3 | 20.6 | 60.7 | 21.1 |
| Amplitude | 0.097 | 0.043 | 4.1 | 2.1 | 12.4 | 5.3 |
| Phase (1880) | −16° | −55° | 170° | 43° | −117° | −67° |

proposed that the Atlantic Ocean integrates NAO and produces the AMO, furthermore, the integral kernel depends on ENSO index [19]. We checked it by simple integration of NAO index. The integrated curve is in a quite good agreement with AMO according to references [17,18] and, thus with the 60-year component of temperature changes, attributed to AMO.

So, as far the troposphere seems to control quick climatic oscillations (below 20 years), the ocean, because of its huge thermal inertia would control the longer term ones.

## 4. The Earth rotation connection

For length-of-day (LOD) we complete the C01 values (downloaded from IERS EOP Product Center WEB site http://hpiers.obspm.fr/eop-pc/), only available from 1962, by JPL's series [20] based on lunar occultations and eclipses, and beginning in 1832. Corresponding LOD values are shown along with detrended and inverted temperature changes in Fig. 3 since 1846. Both present an overwhelming correlation at 60-year period. This was already noticed in Lambeck's monography [21], but did not receive any explanation. A recent but not decisive interpretation was proposed in references [22], where inner core is supposed to induce multi-decadal changes in both Earth rotation and climate.

At shorter time scale, from 1962 to nowadays, the LOD variability is more precisely captured by atomic clock technology and space geodesy, as shown by Fig. 4. There the zonal tides effects have been subtracted according to [23]. The remaining high-frequency part (less than 1 year) is almost completely explained by the momentum exchange with atmosphere (atmospheric angular momentum (AAM) curves comparison at the bottom) [24].

The Fig. 4 confirms that LOD variability also demonstrates anti-correlation with 20-year component (PC 2) of temperature anomaly and sea level, as first noticed in reference [25].

However, nor the (AAM) neither the oceanic angular momentum (OAM) present such multi-decadal trends [26] (see section 5). Therefore we are lead to assume others factors, possibly combining tidal effects with the 18.6 year Moon orbital precession and internal processes at the core-mantle boundary. Indeed, at decadal and multi-decadal scales, it is commonly supposed that LOD changes are caused by angular momentum exchange between core and Earth's mantle. Correlations with the magnetic field variations [26] hint that the process stems from transports of melted metal entertained by dynamo process generating geomagnetism. This lead some authors to hypothesise that multi-decadal changes in both climate and LOD are related to the magnetic field and core-mantle interaction [22,27] or to the Moon orbital precession-induced changes [24,28,29].

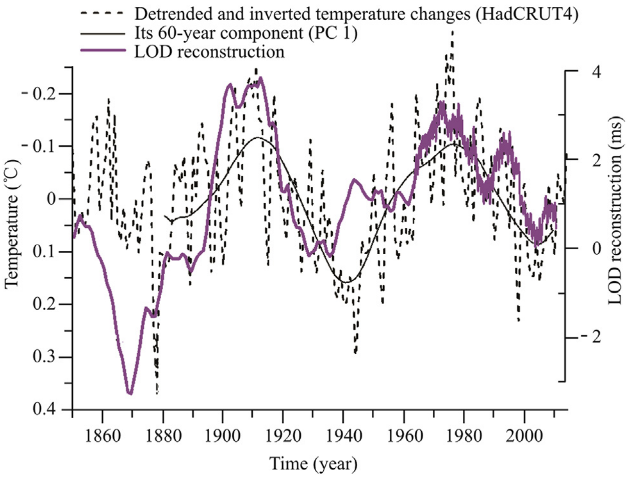

**Fig. 3 – Long-term LOD compared with detrended and inverted temperature changes.**

Whereas oceanic processes is supposed to have a minor impact on LOD, it has to be pointed out that the largest part of LOD trend theoretically originates in the ocean tidal energy dissipation.

As for LOD, Earth's polar motion (PM) is taken from the IERS C01 time series sampled at 0.05 year interval from 1846. The PM trend relation with climate, in particular, with post-glacial rebound, hydrology, etc. is out of doubt [30], we do not consider it.

With a period of approximately 433 days Chandler wobble (ChW) is the crucial component of the polar motion. Its amplitude variability has been extensively investigated: very small in 1930-s, it has also strongly decayed in 2010-s (Fig. 5, left) [25,31,32]. Such repetitive decay requires explanation and our epoch is very important for shedding the light on the Chandler wobble nature. The envelope of the Chandler amplitude shows a significant correlation with the 60-year *SL* component (Fig. 6, right). Another featuring quantity is the Chandler wobble excitation. Let $p(t) = x(t) - iy(t)$ ($x,y$ – coordinates of the pole) be the complex trajectory of the pole, the linear Liouville equation [21,33] states that

$$\frac{i}{\sigma_c}\frac{dp(t)}{dt} + p(t) = \chi(t) \tag{2}$$

where the right-hand side $\chi(t) = \chi_x(t) + i\chi_y(t)$ is called input excitation function, the complex Chandler angular frequency $\sigma_c = 2\pi f_c(1 + i/2Q)$ depends on the real Chandler frequency $f_c = 0.8435\ \mathrm{yr}^{-1}$ and the quality factor $Q \approx 100$, which

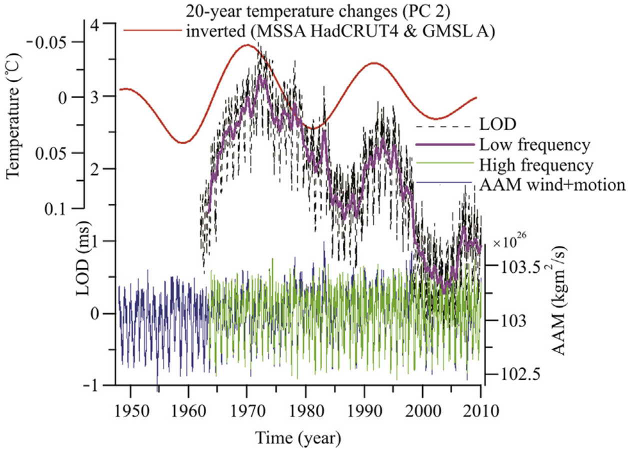

**Fig. 4 – LOD since 1962 compared with 20-year temperature changes (inverted). High frequency component is mostly caused by the AAM (mass + motion) variations (bottom).**

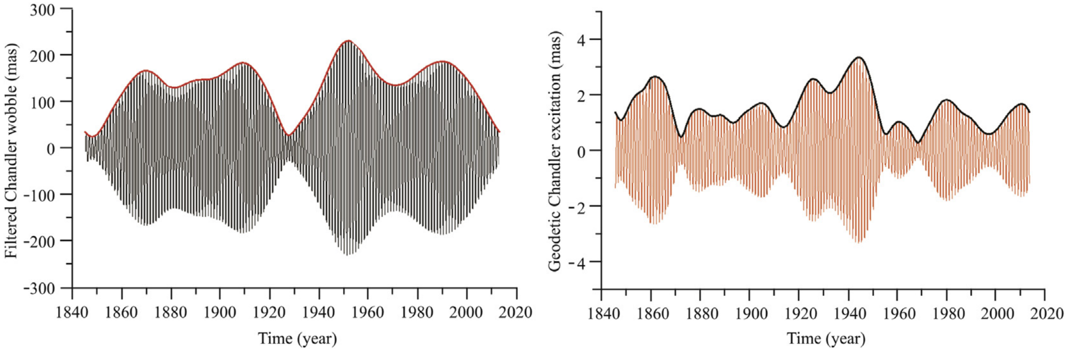

**Fig. 5 – Filtered Chandler wobble (left) and its input excitation (right). The envelope of the 433-day carrying frequency is emphasized.**

empirically determines the damping. The left-hand side is called the geodetic excitation (compare with equation (1)). Its component at Chandler frequency can be obtained by the Panteleev corrective filtering [34], as shown in Fig. 5, right. We readily note that the Chandler excitation presents a quasi 20-year amplitude modulation, superimposed on a longer-term one (approximately 70-year). In reference [34] a possible link with the 18.6-year tide caused by the lunar nodes precession was discussed. Here we focus on the approximately 70-year variation, inherent in both excitation and response. Note that, according to equation (2), the variation of the Chandler wobble envelope is delayed with respect to that of its excitation, reminding us the delay of the sea level with respect to the temperature for PC 1.

An insight is given by Fig. 6, right, where the Chandler wobble envelope is compared along with the PC 1 of the sea level changes. For the period 1880–2010 their correlation coefficient is $r = 0.72 \pm 0.08$. Fig. 6, left, shows the smoothed Earth rotation velocity (filtered and inverted LOD) and 60-year component (PC 1) of Earth's temperature changes. The correlation amounts $r = 0.92 \pm 0.03$. The plot of integrated NAO index is also presented there. The clearly seen correspondence brings us to the conclusion that Earth rotation variations (LOD and Chandler wobble) could be connected with natural climate oscillations, captured by global temperature and sea level.

## 5. Discussion and conclusion

In this work we used MSSA to decompose global climate indexes, such as global Earth temperature anomalies and global mean sea level. Our attention was not focused on the global warming trends, but on the multi-decadal variations, which contain another source of information on climate dynamics. These oscillations could be among the causes of the presently observed pause in the global warming called “Hiatus” [5]. The presence of 60- and 20-year variations in temperature and GMSL is detected. The 60-year component, related to AMO, shows the 20–30 year delay of the SL changes with respect to the temperature changes. We found several clues hinting the response of air temperature (AMO) to the NAO, integrated by the ocean [17–19]. Russian Institute of Numerical Mathematics Ocean Model (INMOM) [35] gives additional arguments showing that some characteristics of the ocean circulation in North Atlantic precede AMO by about decade.

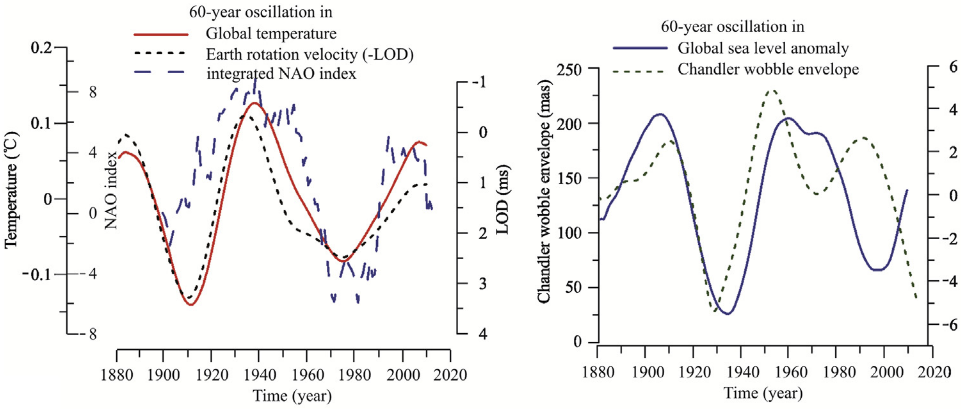

**Fig. 6 – Left: long-term variations of the Earth rotation velocity (filtered and inverted LOD), integrated NAO index, and 60-year component (PC 2) of Earth's temperature changes. Right: Chandler wobble envelope and PC 1 of the sea level changes (GMSL A).**

The comparison of the Earth rotation data with the climate characteristics allowed us to unveil similarities at 60 year period, on one hand between Earth rotation velocity changes and temperature oscillation PC 1 (left panel of Fig. 6), and on the other hand between Chandler wobble amplitude and the SL changes PC 1 (right panel of the same figure).

The Earth rotation parameters (ERP) are in the scope of interests of geodesy and astronomy, they are used to connect terrestrial (ITRS) and celestial (GCRS) reference systems. ERP prediction, quite important for navigation, is complicated, because these parameters are the integrated response to excitation processes in the ocean, atmosphere, and Earth interior.

Milankovitch's theory states that long-term climate variations such as glacial periods are modulated by the orbital parameters and orientation of the Earth rotation axis. This paper extends the interrelation between the Earth rotation and climate variability to shorter time intervals, on the basis of astrometric data (since the middle of the 19 century) and precise observations of the spatial era monitoring both the Earth rotation changes and the evolution of the whole hydro-atmospheric layer.

We sustain the idea that observed similarities between ERP and climate characteristics have a physical basis and makes ERP study meaningful for geophysics and climatology in general. If geodetic community consider mutual influence of ERP and climate variability to be illusive, as its mechanism is unclear by now, works of meteorologist and ocean scientists [4,18,24,25,29,33,36–38] regularly point out that the Chandler wobble, ENSO, NAO, and AMO could be teleconnected. These global climate modes involve deep ocean and atmosphere circulation and are reflected in the global Earth temperature, but the contemporary climate models still hardly reproduce them [37,39]. ENSO, NAO, and AMO simulation and prediction is complicated in reason of their nonlinear and non-stationary dynamics [19]. The ocean angular momentum resulting from these oscillatory modes would be badly reproduced at decadal and multi-decadal timescales, thus explaining why current OAM series do not account for the 20 and 60 year oscillation found in Chandler wobble and LOD.

Possibly, external factors exist which can have similar effects on both of these processes. For example, the change of the gravity coefficient of the Earth $J_2$ under the tidal influence in the 18.6 year Moon orbital precession cycle can change the Chandler wobble frequency $f_c$ and cause its amplitude modulations [40]. Recently we have also found quasi 60-year variations of $J_2$ [41]. Changes of Earth rotation can influence ocean circulation through Coriolis force, but preliminary estimation shows that such effects are small.

The issue could be clarified by further observations of the global processes in the atmosphere, ocean, Earth interior, continuation of GRACE [16,30] and launch of GRACE Follow On mission, enlargement of meteo and oceanographic networks. Even if the causal mechanism is not yet understood, the informational link between the climate and Earth rotation changes can be already postulated. Mutual information found in these processes can help to improve their prediction quality.

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Leonid Zotov, associate professor of National Research University, Highers School of Economics, scientific researcher at Sternberg Astronomical Institute, Lomonosov Moscow State University. Scientific interests: Earth rotation, gravimetry, GRACE, climate change, mathematical filtering.

Christian Bizouard – Director of the «International Earth Rotation and Reference System Service (IERS) Earth Orientation Center», director of the team “Earth Rotation and Space Geodesy” at Observatoire de Paris / SYRTE. Scientific interests: Earth rotation, geophysical excitations, EOP prediction and combination.

Che-Kwan Shum, Professor and Distinguished University Scholar at Division of Geodetic Science, School of Earth Sciences, The Ohio State University. Awardee of the EGU 2012 Vening Meinesz Medal. Fellows of the American Association of Advancement of Sciences (AAAS) and International Association of Geodesy (IAG). His scientific interests include satellite geodesy, sea level science and climate change.