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Consistency of Intra-Centennial Oscillations in Length of Day and Oceanic Characteristics

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Abstract: The paper presents analysis of intra-centennial (inter-decadal and multidecadal) variations of the length of day (LOD) and some oceanic parameters such as sea surface temperature (SST) and sea level (SL). Methods of multivariate regression analysis and correlation analysis are used. Results of the regression analysis show a spatially coherent response of SST to LOD variations on the multidecadal time scale. The earlier response is peculiar to the north and tropical Atlantic where the multidecadal SST variations are approximately opposite to the LOD variations. In the most remaining parts of the oceans, except especially in the Niño 3.4 region of the equatorial east Pacific, the multidecadal SST variations are generally lagged relative to the antiphase variations of the LOD. Smoothing of SST averaged over different areas and of the global mean SL shows that the intra-annual variations include inter-decadal, 20–30-year, multidecadal, 60–70-year, components that correspond to similar oscillation components in the LOD. The most striking correspondence of the two components is observed between the LOD and SST averaged over the Niño 3.4 region. Generally, there are significant correlations of the intra-centennial variations on the averaged and smoothed SST series and global mean SL with the LOD variations. We propose that angular momentum exchange processes involving oceanic circulation and interactions between the Earth's core and the mantle play probably a part in the observed relationships of intra-centennial variations in oceanic parameters with variations in the LOD.

Keywords: length of day, sea surface temperature, sea level, intra-centennial oscillations

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Research Article

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1. Introduction

The Earth includes non-stationary interacting spheres: the atmosphere, the hydrosphere, and the solid Earth, each of which has internal structure. Interactions between the spheres and between different layers in them lead to exchange in angular momentum, which can reflect on the length of day (LOD) that characterizes the angular velocity of the Earth's rotation (AVER) measured from the Earth's surface. Variations in the Earth's LOD varies in a very large range of timescales from days to centuries, due to the action of external torques and exchanges of angular momentum between different parts of the Earth [*Gross*, 2007; *Holme*, 2015]. *Marcus et al.* [1998] proposed that the sub-decadal changes in the LOD were largely controlled by variations in the atmospheric zonal circulation, and the induced changes in the oceanic circulation also contributed to LOD variations. *Chen* [2005] showed an importance of taking into account a mass balance among the atmosphere, ocean, and continental water in this problem and concluded that, on the seasonal timescale, the combined seasonal oceanic and hydrological contributions to the LOD variations could not explain the residual LOD variations unaccounted for by the atmosphere. According to the study by *Jin et al.* [2011], the seasonal and intra-seasonal LOD variations cannot yet be fully attributed to the circulation and mass redistribution at the Earth' surface.

On the longest timescales, the centennial trend in the LOD is produced by tidal drag of the Moon and Sun on the rotating Earth

Although LOD variability on intra-centennial timescales is generally worse understood, variations on inter-decadal (20–30 years) and sub-centennial (60–90 years) timescales, which present in historical observations of geomagnetic field and in main field models are confidently attributed to the Earth's core-mantle interactions [*Jackson et al.*, 2000; *Stefan et al.*, 2017]. *Stefan et al.* [2017] found theses variations also in radial magnetic field evolution at the core surface.

Mound [2005] considered a model of torsional oscillations in the core-mantle system including different coupling mechanisms between the core and mantle such as electromagnetic, topographic, and gravitational couplings. In this model, a fluid torque was applied at the core-mantle boundary. The authors found that when the model includes also a torque applied directly to the inner core, the gravitational coupling between the mantle and inner core in presence of a weak electromagnetic friction at the mantle-core boundary produced oscillations in the LOD with periods of about 20, 30, and 60 years.

The Earth climate system is affected by various external and internal factors. The latter involve complicated interconnections between components of the climate system. Much attention in scientific publications is paid to climate variability of intra-centennial scales (from interdecadal to multidecadal scales), in particular, to 20–30-year and multidecadal (50–85-year) patterns of variability. Such quasi-periodic patterns are found in various climatic parameters including the sea level and sea surface temperature (SST). In particular, cycles with duration of 20–30 and 50–85 years are distinguished in climate parameters and the length of day [*Chambers et al.*, 2012; *Enfield et al.*, 2001; *Mazzarella*, 2008; *Zotov et al.*, 2016].

In a number of papers, relationships between intra-centennial variations of the LOD and climate parameters were studied [see e.g., *Chambers et al.*, 2012; *Mazzarella*, 2008; *Zotov et al.*, 2016]. *Zotov et al.* [2016] supposed the existence of such variations in climate parameters and their assumed relation to the angular velocity of the Earth's rotation (AVER).

Separate narrow-band components of intra-centennial climate variability were isolated by different methods such as the multichannel singular spectrum analysis [*Zotov et al.*, 2016] and correlation analysis with preliminary filtering by ten-year or 23-year running averaging [*Enfield et al.*, 2001; *Mazzarella*, 2008]. In particular, *Zotov et al.* [2016] identified the 20- and 60-year variations in the global mean Earth's surface temperature, the global mean sea level (GMSL), and the LOD. *Mazzarella* [2008] found 60-year variations in the global mean sea surface temperature (GMSST), the atmospheric zonal circulation, the geomagnetic *aa* index, and the LOD. A high correlation between all these components has been obtained. In particular, the correlation coefficient between GMSST and the LOD was equal to −0.97 at a 4-year lag of the GMSST behind the LOD.

Chambers et al. [2012] found a significant oscillation with period around 60-years in records of the tide gauges in every ocean basin in the past century. *Parker and Ollier* [2015] found the quasi 60-year cyclicity in the Arctic air temperature and sea ice extension during the past century. All the above mentioned papers provide also references to other works which confirm the existence of quasi-periodicity or cyclicity in climate processes on the multi-decadal scale.

Variations of SST throughout the North Atlantic include a large amplitude coherent oscillation with period of 65–80 years called the Atlantic Multidecadal Oscillation (AMO) [*Enfield et al.*, 2001; *Knight et al.*, 2006]. The relationship is noticed between the AMO and various regional climatic parameters such as near-surface air temperature and precipitation in the North Atlantic and in the North American and European summer climate [*Knight et al.*, 2006].

Complexity of the physical relationship between the ocean level and the AVER was recognized due to the "Munk's enigma" that pointed to inconsistency between the long term AVER decrease, the amplitude and orientation of the Earth's axis, and the sea levels increase in the twentieth century [see e.g., *Church and White*, 2011] due to the thermal expansion of the ocean and melting of the land ice sheets [*Munk*, 2002]. *Mitrovica et al.* [2015] for the first time have shown that this problem can be fixed by taking into account for the exchange of angular momentum between the Earth's liquid outer core and the mantle, which provides an additional deceleration of the AVER. Thus, the contributions of the thermal expansion of the ocean and the distribution of water masses between the continents and the ocean to the long term trend of the AVER deceleration is supplemented by the effect of the exchange of angular momentum between the Earth's shells.

There are various assumptions about external factors that can contribute to quasi-periodic variations in the sea level, SST, and the AVER. *Zotov et al.* [2016] found that the Chandler wobble envelope reproduces the form of the 60-year oscillation noticed in the GMSL (Chandler wobble is the oscillation of the Earth's axis with period varying between 416 and 433 days). *Mazzarella* [2008] supposed that an increase in solar corpuscular activity caused, with a 5-year lag, a decrease in the zonal atmospheric circulation, which in turn cause variations in the LOD and then in global SST with a 4-year lag behind the LOD.

We believe that the relationships between the intra-centennial variations of climate parameters and the AVER on intra-centennial timescales could be due to more complicated, multi-factor interactions. In particular, the LOD, GMSL and GMSST can be additionally affected on intra-centennial scales through processes that, in particular, include two-way exchange of rotational momentum between the solid earth and the ocean.

The aim of this paper is to analyze the relationship of LOD fluctuations with variations of SST and the sea level and to identify their consistency on the intra-centennial scales.

2. Data used

The following data are used in the work:

1. The excess of the LOD to 86,400 s (LOD anomalies), for 1623–2018 from the International Earth Rotation and Reference Systems Service.
2. Two sets of the GMSL reconstructions: for 1880–2018 by Universität Siegen, Gemany, and for 1880–2013 created by *Church and White* [2011].
3. Global mean SST and tropical mean (20 °S–20 °N) SST for 1850–2020 from Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadsst4/data/download.html).
4. Met Office Hadley Centre gridded data set (HadISST) of monthly SST for 1870–2018.
5. Area averaged SST in the equatorial region 5 °S–5 °N, 120–170 °W, which is the Niño 3.4 index, for 1870–2018, from NOAA.
6. The AMO index, which reflects the multidecadal variability of SST averaged over the North Atlantic, for 1956–2018, from NOAA.
7. Geomagnetic *aa* index for 1868–2020 from the International Service of Geomagnetic Indices.
8. Sunspot number data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels.
9. Aerosol optical depth from NASA Goddard Institute for Space Studies.

The sunspot and aerosol data are only used as predictors in the regression model (see below).

All the data are available at Internet sites. LOD anomalies: https://www.iers.org/IERS/EN/Science/EarthRotation/LODsince1623.html (International Earth Rotation and Reference Systems Service) and http://astro.ukho.gov.uk/nao/lvm/ (Her Majesty's Nautical Almanac Office (HMNAO)). GMSL reconstructions: https://www.eea.europa.eu/data-and-maps/data/external/reconstructed-global-mean-sea-level (Universität Siegen, Gemany) and https://www.csiro.au/en/education/resources/educational-datasets/reconstructed-global-mean-sea-level (The Commonwealth Scientific and Industrial Research Organisation (CSIRO)). Global mean SST and tropical mean (20 °S–20 °N) SST and gridded data set (HadISST): https://www.metoffice.gov.uk/hadobs/hadsst4/data/download.html (Met Office Hadley Centre). SST in the equatorial Niño 3.4 region and the AMO index:

https://psl.noaa.gov/gcos_wgsp/Timeseries/) (NOAA ESRL Physical Sciences Laboratory). Geomagnetic *aa* index: http://isgi.unistra.fr/data_download.php (International Service of Geomagnetic Indices). Sunspot number data: http://sidc.oma.be/sunspot-data/ (World Data Center SILSO, Royal Observatory of Belgium, Brussels). Aerosol optical depth: http://data.giss.nasa.gov/modelforce/strataer (NASA Goddard Institute for Space Studies).

3. Analysis methods

Two main methods are used for the analysis: multivariate linear regression and cross-correlations [see e.g., *Thomson and Emery*, 2014]. The regression method is used to identify regional features of the relationship between SST and the LOD.

The linear regression model written in matrix form [see e.g., *Draper and Smith*, 1998]:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon},$$

where $\mathbf{Y}$ is a vector of observations (series under analysis that is SST) of length n, $\mathbf{X}$ is an $(n \times p)$ matrix of predictors (independent variables), p is the number of predictors, $\boldsymbol{\beta}$ is a vector of unknown coefficients (desired regression coefficients) of length p, $\boldsymbol{\varepsilon}$ is a vector of errors (residuals) of length n. The overestimated system of the equations ($n > p$) is solved by the least squares method.

The regression model includes as predictors the constant, the linear time function (linear trend), the annual mean sunspot number (to account for changes in SST associated with the 11-year solar cycle), the stratospheric aerosol optical depth (to account for the impacts on temperature of the shielding effect of volcanic aerosol), and the annual mean values of LOD. The solar cycle and stratospheric aerosol effects are taken into account since they can affect SST [*Gray et al.*, 2013; *Gruzdev and Bezverkhnii*, 2019].

The solar cycle effect in SST can lag behind the cycle itself. For this reason, the regression model includes not one, but two indices of solar activity (sunspot number). The second index is obtained by shifting the actual index forward in time by a value at which there is no correlation between the shifted and actual indices, that is, they are mutually orthogonal (independent). The shift is determined based on the monthly mean sunspot data. For the period 1870–2018, the shift is found to be 34 months, which, being multiplied by 4, gives 11.3 years that corresponds well to the average value of the solar cycle period.

Similarly, the effect of LOD variations on SST in the regression model is represented by two indices: the actual and shifted LOD values. The condition of their orthogonality in the interval of 1870–2018 is met at the shift of 21 years. If the LOD variations were harmonic, then such a shift would correspond to an oscillation period of 84 years. Despite the fact that this value is quite consistent with the scale of the multidecadal LOD variations, it can only be considered as a very rough estimate of the period of dominant LOD variations.

The number of the predictors in the regression model, $p = 7$. We are interested in two regression coefficients that correspond to the responses of SST to direct and orthogonal (time-shifted) LOD impacts.

Based on responses to the direct impact and to the impact that is orthogonal it, it is possible to estimate approximately the magnitude and phase (lag) of the total response [*Gruzdev and Elokhov*, 2021; *Savinykh et al.*, 2021]. However, applying this technique to the LOD effect, we will keep in mind that the lag is estimated based on a fixed value of the period of 84 years. For this reason, we are primarily interested not in the exact values of the lag, but in its regional features.

The amplitude of the (lagged) total response to cyclic impact is calculated as the square root of the sum of squared responses to the direct and shifted (orthogonal to the direct one) impacts [*Gruzdev and Elokhov*, 2021]. We impose the conditions that the lag must not be negative and must not exceed the half-period of the variation (42 years for the LOD). Therefore the value (amplitude) of the total response is positive if the SST response to the LOD shifted by the lag value is in phase with the LOD. Otherwise the value (amplitude) of the total response is negative if the SST response to the LOD shifted by the lag value is in antiphase with the LOD.

To solve the system of equations of the regression model, we used the method taking into account the presence of memory in the observational data in a large range of time scales [*Gruzdev*, 2019a,b]. In the problem of regression analysis, the memory manifests itself as an autocorrelation of the residual series (error), which leads to a reduction in the number of degrees of freedom that affect the confidence of regression estimates. This method allows us to correct the regression estimates and their confidence intervals, using the representation of the correlated residual series as an autoregressive process, the order of which can be very large. The results presented in this paper, as in paper by *Gruzdev* [2019a], are obtained with the order of the autoregressive process equal to 50.

Before the cross-correlation analysis, the data (except the LOD) are smoothed by the running Kaiser-Bessel window that has a shape close to the Gaussian curve [*Cappellini et al.*, 1978]. From the GMSST and GMSL data, quadratic trends were previously removed. The Kaiser-Bessel window provides minimal "percolation" of high-frequency components, which is essential when identifying the form of intra-centennial variations. For smoothing, we use the Kaiser-Bessel window with the cut-off frequency corresponding to the 10-year period. Unlike *Enfield et al.* [2001] or *Zotov et al.* [2016], we do not assume in advance that there is certain, for example, near 60-year cyclicity in the parameters under consideration.

4. Results of the analysis

Let us first consider the results of the multivariate regression analysis. We are interested in the SST response to LOD variations in different regions of the world ocean. For convenience of presenting the regression analysis results, the regression coefficient corresponding to the LOD is multiplied by the scale factor equal to the LOD standard deviation. Figure 1 shows the distributions of the SST changes associated with the multidecadal LOD variations and the corresponding lag of the SST changes behind the LOD variations. Both the amplitude and the lag depend on region.

Areas of strong SST response to the multidecadal LOD variations are noted in the equatorial east Pacific, mid-latitude North Atlantic, and mid-latitude Pacific. In this paper we are primarily interested in the ocean regions associated with the El Niño/La Niña events and the AMO.

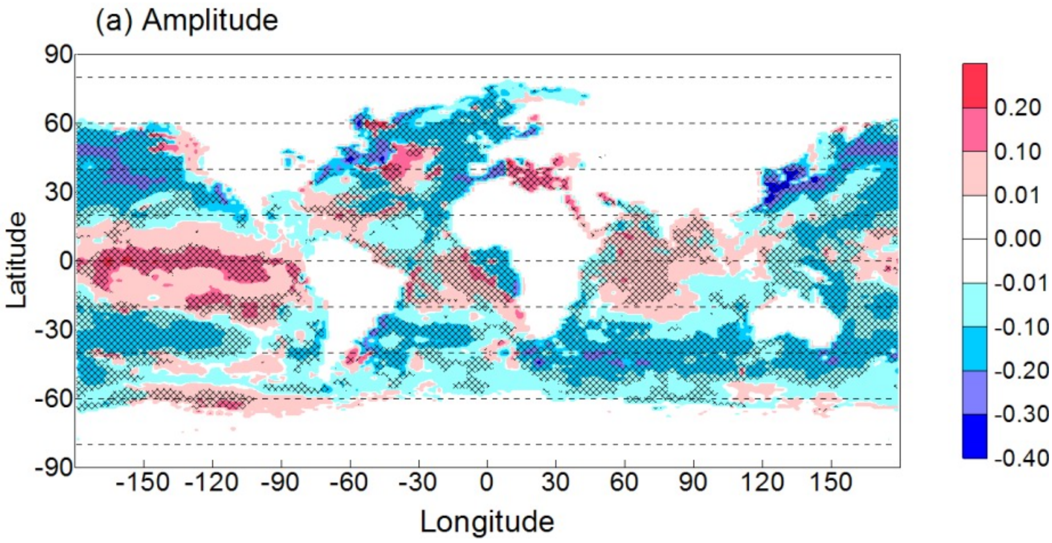
First of all we note a specific SST response in the equatorial east Pacific region, which is approximately opposite (antiphase) to the mid-latitude SST responses in the eastern part of the Pacific. The equatorial SST response lags by 10–20 years relative to the LOD variations. The lag in the Niño 3.4 region is, on average, about 15 years.

The SST variations in the equatorial parts of the west Pacific, the Indian Ocean, and the Atlantic are approximately opposite to the LOD variations (one should take into account the sign of the amplitude). There is no significant difference in SST lags between these regions and the adjacent mid-latitude parts of the oceans. The mid-latitude SST responses there lag relative to the antiphase behavior, and the lag is mainly confined within a decade.

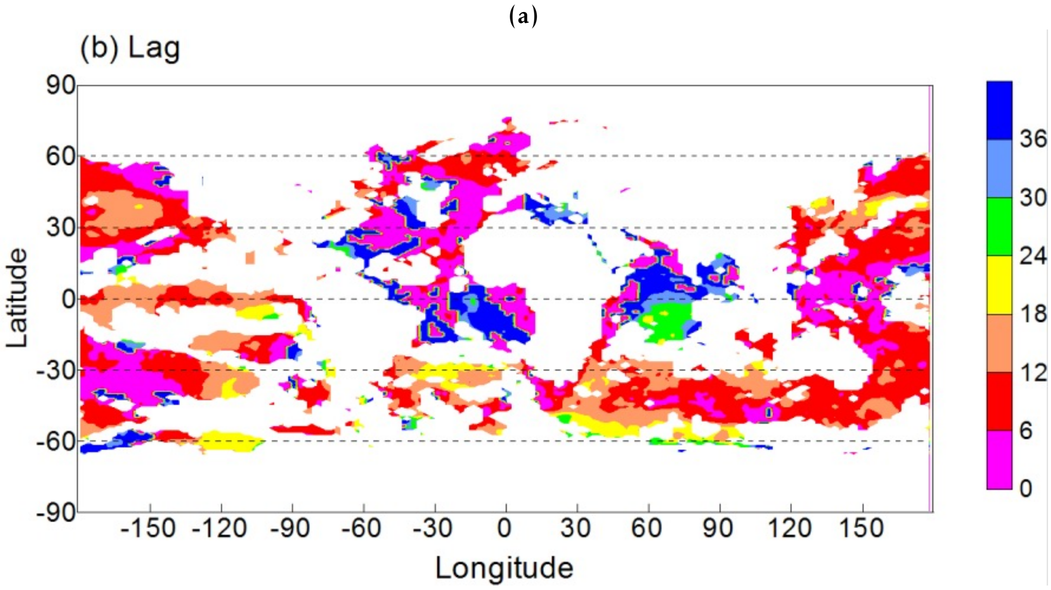
In addition to the relationship between the LOD and SST that interests us, more general conclusions may be deduced from Figure 1. It demonstrates the existence of the multidecadal oscillation in SST on regional and global spatial scales. The early phase of the oscillation is observed in the north mid-latitude and tropical Atlantic Ocean, while the generally later phase is characteristic of other oceans (except the equatorial east Pacific). The globally spread multidecadal oscillation is spatially coherent, with oscillations in different regions linked by certain phase relations.

Let us now consider in more detail the relationships of the LOD with regional and global oceanic parameters. Figure 2 shows variations of the LOD, the Niño 3.4 and AMO indices, the GMSL, the tropical mean SST (TMSST), and the GMSST. It should be noted that the smoothed variations in Figure 2 do not contain leaked high-frequency components in their spectra (we do not give a figure for the spectra), while such components percolate when smoothing by a rectangular window with the same (0.1 year^{-1}) cut-off frequency.

The LOD variations (Figure 2a) include at least two components of intra-centennial scales. One has the period of about 65 years and is presented, for example, by maxima in



(a)



(b)

Figure 1. (a) Amplitude (°C per LOD standard deviation) and (b) lag (years) of the SST response to LOD variations. Areas of statistically significant (95%) amplitude values are shaded. Lag is only shown for statistically significant response.

1910 and 1975. The period of the other component is 20–30 years. We note, by the way, small amplitude of the smoothed curve in Figure 1b compared to the unsmoothed curve, which could affect features of the smoothed curve if inappropriate window would be used for smoothing.

The graph of the Niño 3.4 index (Figure 2b) differs markedly from the TMSST and GMSST graphs (Figure 2e, 2f). The smoothed variations of the AMO index (Figure 2c) are similar in shape to the TMSST and GMSST variations (Figure 2e, 2f).

The GMSST and the North Atlantic mean SST (the AMO index) are characterized by large amplitude intra-centennial variations (Figure 2c, 2f). In a number of publications [see, e.g., *Chambers et al.*, 2012; *Enfield et al.*, 2001, and references therein], the main cycle of 60–70-year period was only detected in these parameters. The intra-centennial scale variations of these parameters in Figure 2 have four broad local extremes corresponding to the opposite sign extremes of the LOD in 1870, 1910, 1930, and 1975. The intra-centennial components of the GMSST and the AMO make approximately the same contribution to the total variances of these parameters as the interannual variability does.

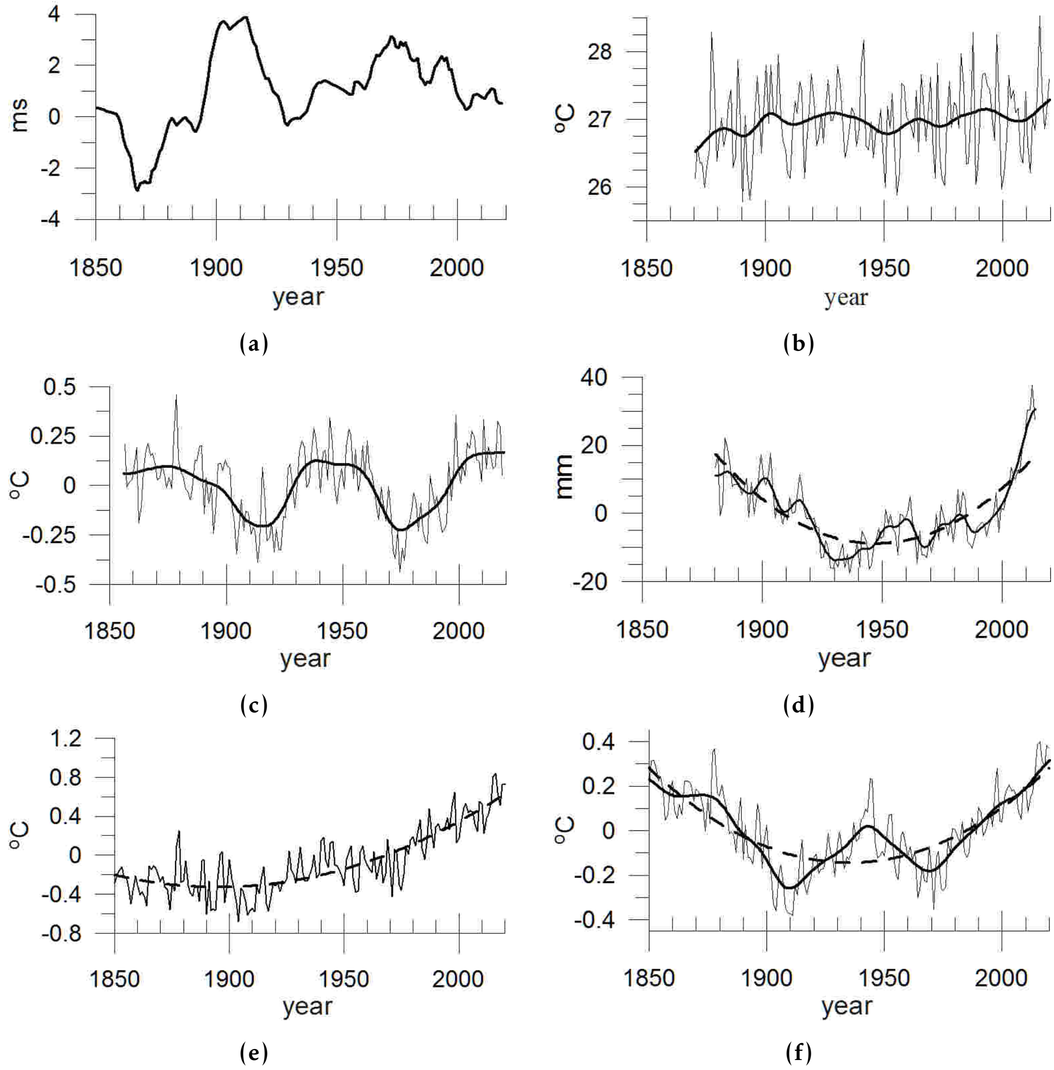


Figure 2. (a) LOD anomaly, (b) SST (Niño 3.4) and (c) AMO indices, (d) global mean sea level (linear trend removed), (e) tropical mean SST anomalies, and (f) global mean SST (linear trend removed). Thin and thick curves in plots (b–f) show unsmoothed and smoothed values, respectively. Dashed curves are quadratic trends.

Notable quadratic trends in Figure 2 determined by the least squares method show that in these variables, in addition to intra-centennial variations, there are variations which time scale exceeds 300 years. Removal of the trend from does not affect the spectral composition of the intra-centennial scale.

We estimate cross-correlations of the LOD oscillations with the detrended smoothed SST variations in the Niño 3.4 region, in the North Atlantic, and in the tropics as well as with the GMSL variations. The extremes of the cross-correlation functions and the corresponding lags are given in Table 1. The 2nd and 3rd columns in Table 1 correspond to two periods for which cross-correlations are estimated. One period is the full period common for a pair of correlated quantities (an oceanic parameter and the LOD). The other period is a full period minus the last ten years. Periods in Table 1 are linked to the LOD. Therefore the actual periods corresponding to parameters lagging relative to the LOD are shifted by lag values.

The combination of a near zero lag end a negative extreme value of the correlation points to opposite (antiphase) variations of signals. Table 1 shows that the smoothed GMSST variations are synchronous with LOD, while the variations of other parameters lag behind the LOD variations. All correlations in Table 1 are fairly high, about 0.6–0.7 in the

Table 1. Extreme values of the cross-correlation function between the detrended smoothed variations of the oceanic parameters and the LOD variations, their standard errors, and the corresponding lags (in years, in parentheses) of the variations of the parameters relative to the LOD variations. Column 2 is for the whole observational periods, while column 3 is for the periods without the last ten years. Periods are related to oceanic parameters

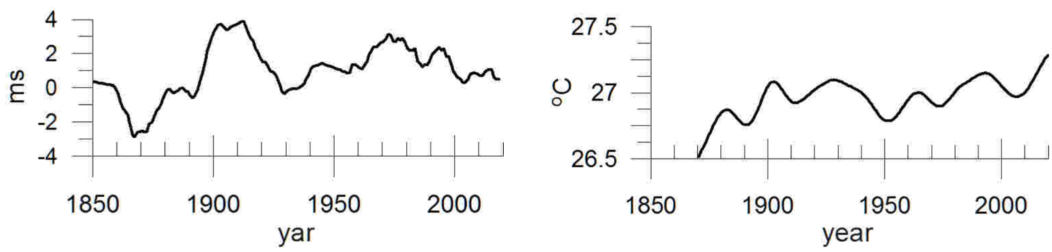
Niño 3.4 index	1870–2019 0.67 ± 0.12 (20)	1870–2009 0.69 ± 0.12 (19)
AMO index	1856–2019 −0.71 ± 0.16 (4)	1856–2009 −0.74 ± 0.15 (4)
TMSST	1850–2020 0.58±0.24 (36)	1850–2010 −0.58 ± 0.21 (4)
GMSST	1850–2020 0.76±0.22 (37)	1850–2010 0.74 ± 0.22 (37)
GMSL	1880–2018 −0.59 ± 0.24 (24)	1880–2008 −0.69 ± 0.20 (23)

absolute value. The 20-year lag of the intra-centennial variations of SST in the Niño 3.4 region relative to the LOD variations is applied in Figure 3 that shows a good consistency of the two parameters.

These SST variations reflect the structure of the LOD curve and contain the both inter- and multidecadal components inherent to the LOD variability. In the 130-year interval, the cross-correlation between LOD (1860–1991) and SST in the Niño 3.4 region (1879–2010) increases up to 0.8.

The ~ 20-year lag of the mean SST variations in the Niño 3.4 region estimated from cross-correlations is of the same order of magnitude as the ~ 15-year lag derived from the multivariate regression analysis (Figure 1b). Approximately antiphase variations of the AMO index and the LOD (see negative extreme at small lag in Table 1) agree with the results of the regression analysis. Table 1 shows that the intra-centennial variations of the TMSST and GMSST are opposite to the LOD variations. This does not contradict the results of the regression analysis in Figure 1 if we take into account smallness of the Niño 3.4 area compared to the global and total tropical areas.

Let us now consider in more detail the intra-centennial variations of the other oceanic parameters: GMSL, TMSST, and GMSST with quadratic trends removed (see Figure 4). The shapes of these variations can be judged from Figure 4a–4d compared to Figure 4a that is an inverse plot of the LOD. The multidecadal component is very evident in all the parameters. The shorter component is also seen in the TMSST and GMSL. Herein, the lagged GMSL variations are consistent with the LOD variations over the two components. We note that the lags of the Niño 3.4 index and the GMSL relative to the LOD are close to each other (Table 1) and, therefore, the multidecadal variations of the Niño 3.4 index



(a) (b)

Figure 3. (a) LOD and (b) smoothed variations of the SST (Niño 3.4). Plot (b) is shifted left relative to plot (a) by 20-year points.

and the GMSL are approximately in antiphase to each other. The correlation for the GMSL increases if the last ten years are excluded. The lack of correlation between the GMSL and LOD variations at the right edge of the time period is due to the significant difference in amplitudes of the variations (compare Figure 4a and Figure 4b). One probable reason of this is an acceleration of the GMSL increase after 2000 clearly seen in Figure 2d, which has been superimposed on the positive phase of the multidecadal variation of the GMSL. A speedy increase in the GMSL could be caused by the accelerated melting of the ice sheets

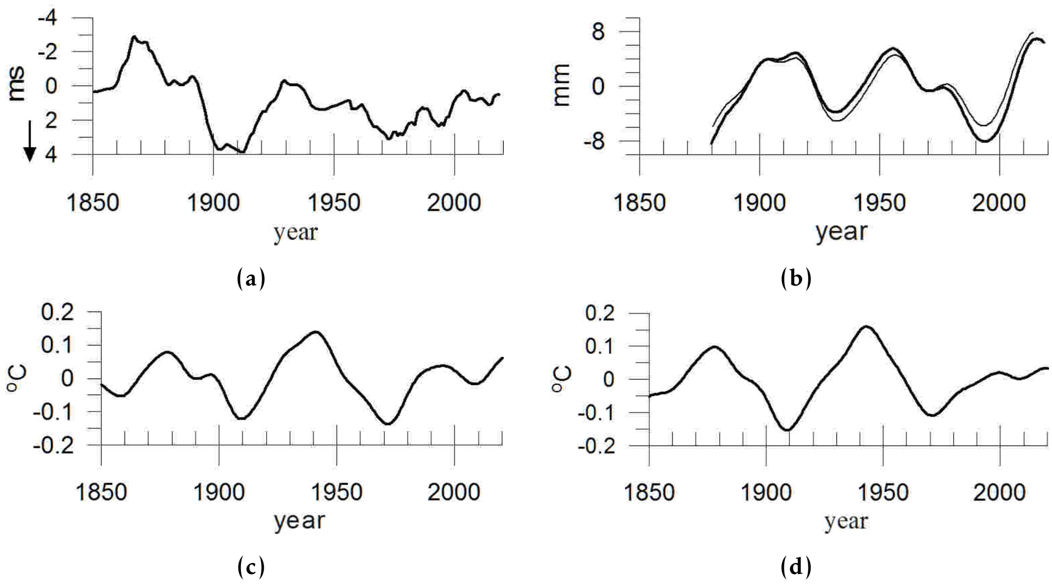


Figure 4. (a) LOD and intra-centennial variations of (b) the global mean sea level, and (c) the global mean and (d) tropical mean SST. The plot (b) is shifted left by 23-year points relative to others. Two curves in (b) correspond to two data sets. The thick curve corresponds to CSIRO data. The vertical axis in (a) is directed downwards.

Comparing Figure 2f to Figure 2d and Figure 4d to Figure 4b we note that the GMSL increase after 2000 is not accompanied by similar increase in SST.

In summary, the analysis has shown consistency of intra-centennial variability in the oceanic parameters (SST and the GMSL). Besides, there is consistency of the ocean variability with variations of the LOD. It is most impressively demonstrated by the consistent changes in the LOD and the Niño 3.4 index.

5. Discussion of the results

The results reported show the existence of statistical relationships between the LOD, on the one hand, and SST and the GMSL, on the other hand. Some considerations on physical base of the relationships are proposed in papers referred to in Introduction.

The distinct and most straightforward relationship between the LOD and the averaged SST (GMSST, TMSST) at near zero lag could have an explanation in terms of thermal expansion of the ocean if the correlations between the LOD and these parameters would be positive, which implies that the expansion should result in decrease in the AVER, i.e. in LOD increase. However the relationship is just the opposite. Therefore we have to admit that the mechanism of the relationship between SST and the LOD is much more complicated.

The relationship between the LOD and the intra-centennial GMSL variations is completely different from the one that could be deduced from mechanistic application of the law of rotational momentum conservation. Moreover, the LOD variations lead the GMSL variations (Figure 4) but not vice versa. It is likely, nevertheless, that this does not necessarily points to the LOD variations as a cause and the GMSL variations as an effect, since in a nonlinear system, a phase lag is an uncertain indicator of the direction of a causal relationship. However, we have estimated that the effect of the GMSL change by 10 mm (see Figure 4b) on the LOD is negligible compared to LOD variations in Figure 4a.

A close relationship between the LOD and GMSL variations indicates that there might be a common reason for them. The consistency of the LOD and GMSL variations is all the more interesting given that the ocean level is affected by diverse factors that can override the effect, somehow related to fluctuations in the AVER.

Relation of the LOD to the angular momentum exchange processes in the Earth is proposed on the decadal and shorter time scales as well [*Gross*, 2007; *Holme and de Viron*, 2013]. *Yang and Song* [2020] conclude from seismic sounding about probable decadal fluctuations in the rotation rate of the Earth's core. *Gross* [2007, Section 3.09.4.1.2] calls the interaction between the mantle and the core the most important mechanism that causes variations of the LOD on decadal timescales. *Gross* [2007] notes that the LOD amplitude "is too large to be caused by atmospheric and oceanic processes". *Holme* [2015] concludes that the LOD variations on decadal timescales almost certainly originate from the exchange of angular momentum on the boundary of fluid core and solid Earth. He reviews model results indicating that large-scale flow in the Earth's core can result in LOD variations on the interdecadal time scale. *Olson* [2016] supposes that proposed mechanisms for the cause of the angular momentum transfer includes pressure forces acting on the core-mantle boundary topography.

Stefan et al. [2017] report that inter-decadal (20–30 years) and sub-centennial (60–90 years) oscillations "present in observatory magnetic flux data and main field models". They remark that sub-centennial oscillation "is responsible for the fine structure of the time evolution of the geomagnetic field at the core-mantle boundary".

Based on this information, we can assume that a link between the LOD and the angular momentum exchange processes in the Earth interior may extend to intra-centennial time scales. This assumption is supported by numerical simulations by *Mound* [2005] referred to above.

The most prominent in the LOD variations is the multidecadal component, and it is it that mainly contributes to correlations of the LOD with the GMSL, GMSST, and TMSST (see Figure 2c and 4 and Table 1). Multidecadal variability is an important feature of the North Atlantic. The AMO that characterizes multidecadal oscillations in North Atlantic SST links closely to the Atlantic Meridional Overturning Circulation, which includes the northward flow in the upper Atlantic and the southward flow in the deep Atlantic [*Zhang et al.*, 2019].

In the tropical Pacific Ocean, there is a system of surface and subsurface zonally directed currents. The swiftest and most coherent is the westward Equatorial Undercurrent [*Philander*, 1973]. It delivers cold water to the eastern Pacific and thus significantly influences SST in this region and maintains the SST zonal gradient across the Pacific [*Drenkard and Karnauskas*, 2014]. Long term changes in the Equatorial Undercurrent are diagnosed to be due to changes in the trade winds in the western and eastern Pacific affecting oceanic zonal pressure gradient and the surface current. The latter influences the Equatorial Undercurrent through vertical friction [*Drenkard and Karnauskas*, 2014].

Both equatorial zonal and extratropical meridional circulations can play part in exchange of angular momentum between the ocean and the solid Earth. Meridional circulation can affect continents due to the Coriolis effect and/or effect on moment of inertia due to redistribution of salt and fresh water. We have estimated the effect of variations of the Equatorial Undercurrent on LOD and found it negligible. Apparently the same is true for other circulation patterns. However, if the global oceanic circulation acts in concert on intra-centennial time scales, as it can follow from the spatial coherence of the multidecadal variations in SST, its effect on LOD could be probably stronger.

The observed SST variability on the intra-centennial scales is poorly simulated by state-of-the-art climate models. *Laepple and Huybers* [2014] show that although there is a general consistency between CMIP5 (Coupled Model Intercomparison Project Phase 5) model simulations and regional SST variability on interannual timescales, the models underestimate significantly the SST variability on larger scales, and the discrepancy is greatest at low latitudes and increases with timescale. *Kravtsov et al.* [2018] show that the discrepancy between model simulations and observations on the decadal and longer scales have a coherent spatial structure of the pronounced Global Multidecadal Oscillation. Moreover, the associated SST anomalies originates in the North Atlantic and spread out to other oceans. This is what we generally see in Figure 1.

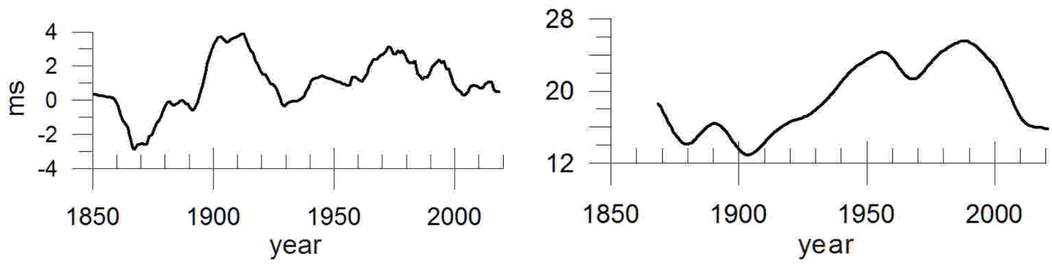
Based on state-of-the-art climate model simulations and observational data, *Mann et al.* [2020] conclude that there is no consistent evidence for decadal or longer-scale intrinsic oscillatory signals that could be distinguished from climatic noise. The probable reason of multidecadal variability is an external (for example, long-term volcanic) forcing.

Whether or not the intra-centennial variations are due to internal climate variability or external forcing, there is a distinct, spatially coherent relationship between the LOD and oceanic parameters. This consistency should have physical explanation. Mechanisms of the relationship may involve interactions between gaseous, liquid, and solid spheres of the Earth.

Regarding the external forcing of the reported intra-centennial variations we note the near 22-year oscillations (Hale cycle) in solar magnetic field [*Owens et al.*, 2015]. Similar variability is peculiar to indices of solar and geomagnetic activity [*Rivin*, 1998].

Results of simulation of the core-mantle interactions by *Mound* [2005] indicate the transfer of angular momentum from the core-mantle boundary to the overlying layers of the Earth. The 20–30-year and multidecadal components are present in geomagnetic fluxes at the core mantle boundary [see e.g., *Mound*, 2005; *Stefan et al.*, 2017].

Intra-centennial variations of the *aa* index of geomagnetic activity compared to the LOD variations are presented in Figure 5.



(a) (b)

Figure 5. (a) LOD variations and (b) intra-centennial variations of the geomagnetic *aa* index.

The correlation between the two is −0.37 at zero lag. Although it is significantly worse than the correlations between the oceanic parameters and the LOD (see Table 1), this does not mean that there is no physical link between the *aa* index variations and LOD. However we do not believe that intra-centennial variations of geomagnetic activity affect the LOD through modulation of the solar corpuscular flux as proposed by *Mazzarella* [2008], which presumably affect tropospheric cloudiness and, as a result, the atmospheric circulation dragging the solid Earth. Geomagnetic activity, as well as the solar corpuscular flux, have much stronger decadal variations caused by the 11-year cycle of solar activity [*Gray et al.*, 2010], but this cycle does not reflect noticeably on the LOD variations (see Figure 1a).

The intra-centennial variations in the LOD are probably contributed to by geodynamic processes in the Earth. If so, there should be physical mechanism of generation of similar variability in the general circulation of the ocean. Its study and attribution of the intra-centennial oceanic variability to variations of the AVER could be done with the help of global circulation models with coupled atmosphere and ocean, in which effects of AVER variations are prescribed. To take into account for feedbacks between the oceanic circulation and the AVER and to characterize an effect of global multidecadal oscillations on the AVER, the models should account for angular momentum exchange between the geospheres.

Regarding a possibility of an external forcing of the near 30-year and 60–70-year variability in the Earth and in the LOD, we may consider recurrence of same orbital positions in the Earth–Sun–Moon system. Consider, for example, the position of the lunar orbit perigee at the moment of the perihelion of the Earth's orbit, which maximizes oceanic tides and solid Earth deformations [see *Christian and Roy*, 2017]. Given the revolve period of the Earth (~ 365.24 days) and the anomalistic period of the Moon revolve (~ 27.55 days), the time interval between such two consecutive positions is close to 62 years. The 62-year rhythm could modulate the gravitational effect on the Earth.

More frequent position is when the Earths is in its perihelion and the Moon observed from the Earth is in its full phase. Given the revolve period of the Earth and the synodic period of the Moon (~29.53 days), we get period of 33 years. This period is close to period of near-30-year variations at the mantle–core boundary discussed above and falls into the 20–30-year tinescale range of the observed interdecadal variations of the LOD.

It is worth noting that the orbital rhythms can also affect the AVER through conservation of the total rotational momentum of the Earth-Moon-Sun system. Gravitational link between the three should influence the individual rotation momentum of the Earth depending on its position relative to the two others. Quantification of such an effect in the LOD requires special study. If the effect would not be negligible, this external excitation of LOD variations could interact with flow variations of the same timescale in the Earth's mantle proposed by model calculations by *Mound* [2005]. We should note however, that *Mound* [2005] obtained intra-centennial variations in the Earth without any assumption of any links with the external gravitational field.

We would also like to note here that a near 66-year period could a period of oscillations at a combination frequency produced by oscillations with periods of about 22 and 33 years. In a nonlinear system, oscillations at the combination frequency can originate without external forcing as a result of nonlinear interaction. One clear example of such oscillations is the distinctive 20-month oscillation in various atmospheric parameters due to interaction of the annual and quasi-biennial cycles [*Gruzdev and Bezverkhnii*, 2006; *Gruzdev and Bezverkhny*, 2000].

One external candidate for excitation of the 60-year oscillation in climate parameters was recently proposed by *Scafetta et al.* [2020]. They found the same oscillation in the Jupiter orbit and in meteorite falls and speculate a similar oscillation in the interplanetary dust influx to the Earth's atmosphere, which could affect the climate through modulation of cloud formation.

6. Conclusions

Analysis has shown the existence of consistency of intra-centennial (interdecadal to multidecadal) oscillations in the length of day, global and regional mean sea surface temperature, and the global mean sea level. The oscillations include interdecadal (20–30-year) and multidecadal (60–70-year) components. The consistency between the LOD and the oceanic parameters is observed over the two components.

The multidecadal oscillation in SST derived by the regression analysis spreads globally and is spatially coherent. There are certain phase relationships between the SST oscillations in different regions. The earlier phase is peculiar to the north and tropical Atlantic where the multidecadal SST variations are approximately opposite to the LOD variations. In the most remaining parts of the oceans, except especially in the equatorial east Pacific, the multidecadal SST variations are generally lagged relative to the antiphase variations of the LOD. The multidecadal SST variations in the equatorial east Pacific lag behind the LOD variations, and the SST variations in this region and in the mid-latitude Pacific are approximately opposite to each other.

The results of the regression analysis have been confirmed by the results of cross-correlation analysis that considers additionally GMSL variations. It shows that the intra-centennial variations of the TMSST and GMSST are approximately opposite to the LOD variations, while the variations of the GMSL and SST in the Niño 3.4 region of the equatorial east Pacific significantly lag behind the LOD variations. If the GMSL lag is considered against variations of the LOD that are opposite to the actual ones, then the GMSL and Niño 3.4 SST lags are close to two decades.

Based on reviewed results of other authors' works we conclude that the observed intra-centennial variations of the LOD are contributed to by geodynamic processes in the Earth. Angular momentum exchange processes involving oceanic circulation and interactions between the Earth's core and the mantle play probably a part in the observed relationships of variations in oceanic parameters with variations in the AVER. We cannot here quantify contributions of these mechanisms. General circulation models and Earth system models with coupled atmosphere, ocean, and earth could help on this way.

In conclusion, we note the newness of this work.

Estimates of the amplitude and phase of the response of SST to LOD fluctuations and their latitude-longitude distribution were obtained for the first time (Figure 1).

A change in ocean characteristics consistent with LOD variations (at a certain delay in the response of ocean characteristics) over the entire intra-centennial scale range (20–90 years) has been shown without splitting into separate oscillation modes.

A noticeable similarity in the shape of the intra-centennial variations of SST in the Niño 3.4 region and LOD (at a delay of SST by about 20 years) has been revealed.

The hypothesis is proposed that the intra-centennial oscillations of LOD (i.e. oscillations of the Earth's rotation velocity) and climate are caused by the processes of redistribution of angular momentum in the Earth shells.

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