Multidecadal and 6-year variations of LOD

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Multidecadal and 6-year variations of LOD

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Abstract.   The subject of our study is 6-, 20- and 60-year oscillations in the length of day (LOD). Spectral and wavelet analyses of LOD time series have been performed, multidecadal harmonics have been adjusted and simple prediction has been made. Input from the variations of the angular momentum of the ocean and the atmosphere into LOD changes at 6-, 20- and 60-year periods has been analysed. We found out that the oceanic forcing (OAM) of LOD at 20- and 60-year scales is less than 20 microseconds, and 6-year oscillation after atmospheric effects subtraction becomes quite stable with the amplitude of around 0.2 milliseconds. To perform filtering, we used Panteleev's band-pass filter. Since multidecadal oscillations with the amplitude up to 3 milliseconds remain unexplained, we compared them with temperature and sea level anomalies, Chandler wobble and its excitation envelope, and with the Earth's magnetic dipole strength anomaly, a number of processes contain multidecadal variations, the signature of which is quite similar to LOD changes.

1. Introduction

Earth rotation is variable. Back in the XVIII century, Immanuel Kant argued that deceleration in the rotation of the Earth could be caused by tidal friction, which implied the increase in the length of day (LOD). Pierre-Simon Laplace later suggested that, according to the laws of mechanics, winds, tides, earthquakes, volcano eruptions and other mass movements on the planet should be responsible for the variability of the Earth's rotation. It was impossible to measure these variations due to the absence of the high-accuracy instruments. In the XIX century, the invention of highly accurate astronomical telescopes allowed measuring the time of the passage of stars across the meridian and determine their equatorial coordinates in astronomical observatories all over the world (e.g. in Paris, London, Pulkovo, Washington, etc.). Angular resolution of these telescopes could reach up to a few tenths of an arcsecond. Over time the observations of the variations in the Earth's rotation have been getting more and more accurate, reaching tens of microseconds today (Fig. 1, right). The ancient information about the speed of the Earth's rotation was extracted from coral reef layers of hundreds of millions of years old. In the XIX century, the astrometry was used for observations, but with the invention of an atomic clock, LOD anomalies started to be measured by comparing observations of the Earth's rotation

with the atomic time scale. From the very beginning, astronomers and geophysicists were interested in analysing data on the rotation of the Earth. N.M. Stoyko noticed the influence of seasonal redistribution of masses on LOD. Over time, the influence of the ocean and the atmosphere was revealed, and a tidal model of the Earth's rotation rate changes was developed (Fig. 2).
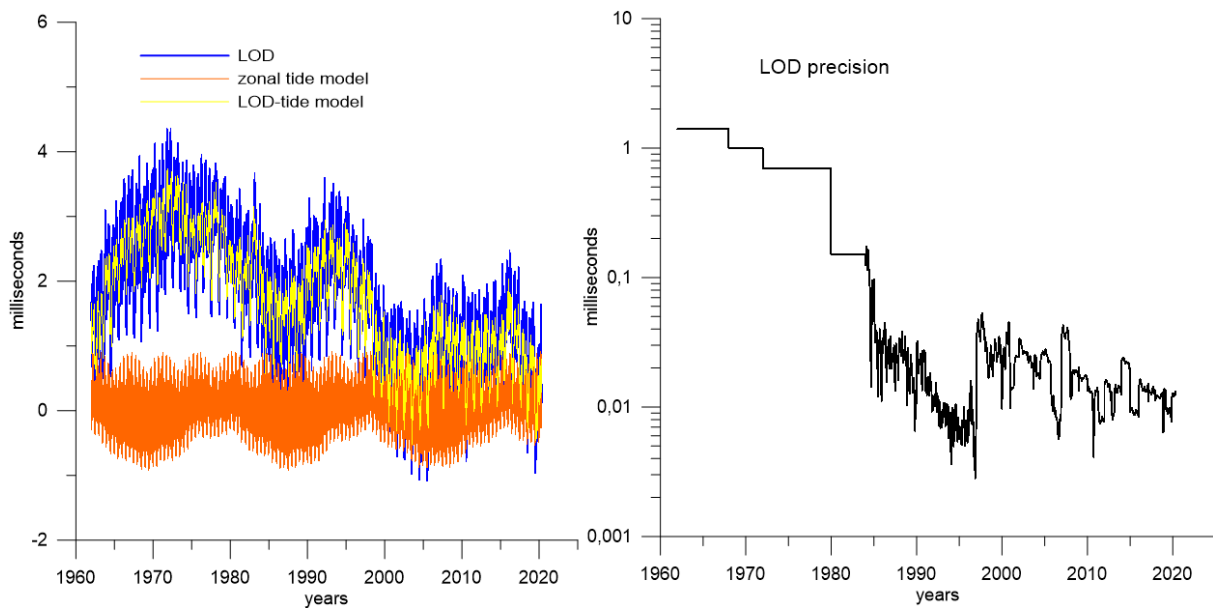

Figure 1. Left: LOD changes (blue) in milliseconds. IERS zonal tides model (orange), and LOD after zonal tides subtraction (yellow-orange). Right: LOD precision.

In last decades the weak 6-year oscillation in LOD appeared in the focus of interest [3, 14, 15] Discovered in 1999 [9], theoretically related with the eigen-oscillations of the Earth's inner core [6, 5], its studies became an important source of information about physical conditions inside the Earth [1]. The question of its amplitude and phase variability is quite important. In [6] permanent decrease of the amplitude of 6-year oscillation was proposed, which led to the conclusion about its free damping and gave estimations of magnetic and viscous properties at the core-mantle boundary. Even more interesting are multidecadal oscillations in LOD. The history of their study is quite long and there have been a number of attempts to relate them with internal processes and climate variability [2, 4, 8, 12]. In this study we analyse the observational data on LOD oscillations in 6-, 20- and 60-year frequency bands.

2. Observational data and spectrum

In our study we use data from EOP C04 bulletin of International Earth Rotation and Reference Systems Service (IERS), containing Earth Orientation Parameters (EOP), including LOD with daily step, starting from 1962, and EOP C02 bulletin with 100-day step since 1830. These time series are in open access on the website of IERS Earth Orientation Parameters Product Center (EOP PC) [17]. It collects EOP, provided by international observatories and is located in Paris. EOP PC internet page has a lot of facilities, written in PHP, it allows to extract data covering different time spans, plot them, compare geodetic and geophysical excitations, compare data from different observation centres and analyse them. We plotted LOD from bulletin C04 in Fig. 1, left.
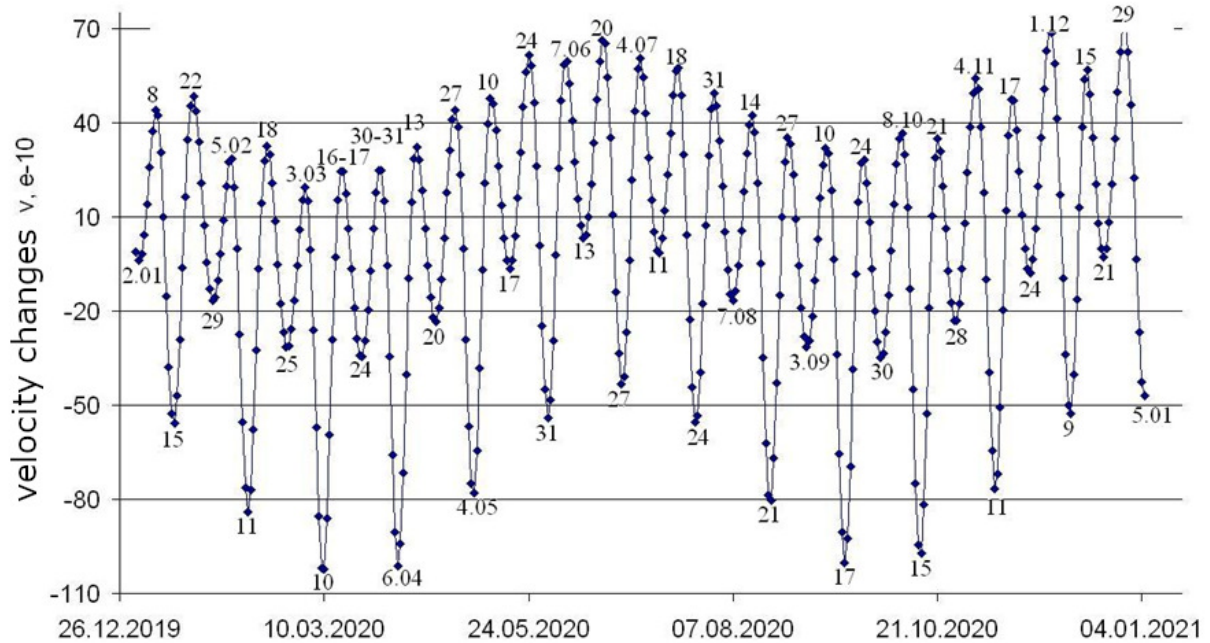
Figure 2. Tidal variations of the rotation velocity in 2020, IERS model.

From Fig. 1, left, it is seen that LOD variations (in blue) span over the periods from days to tenths of years. Well known zonal tides (orange) influence LOD through deformation of the Earth. In particular, when the Moon crosses the equator, the Earth's rotation velocity decreases, and when it reaches largest declinations to the north or to the south – vice versa, minima of LOD are observed (see Fig. 2). According to N. Sidorenkov [10] near this dates of extrema in LOD the abrupt weather changes are more probable. We have observed such change on 17.09.2020 in Moscow with heavy rain and thunderstorms, when the minima was especially strong because it coincided with the New Moon [16]. In Fig. 1, left, the plot given in orange clearly depicts 18-year tidal cycles related to the Moon orbit precession. For example, in 1997 and 2015 the Moon orbit was between ecliptic and equator, thus the Moon could reach declinations up to $\pm 18^o$ only. In 1988 and 2007 its orbit had larger angle with equator, than the ecliptic, and Moon declinations could be up to $\pm 28^o$. This paper examines LOD oscillations after zonal tides were subtracted. Even after that, the long-period oscillations remain in LOD. Three maxima in 1972, 1994 and 2016 in Fig. 2 are quite near the maxima of the tide, but are not explained by its model. As it will be shown below, long-term LOD variability cannot be explained by the oceanic and atmospheric influence either, thus traditionally it is related to the angular momentum exchange in the Earth interior.

Let's perform wavelet and spectral analysis of LOD. Wavelet scalogram of C02 series is presented in Fig. 3, of C04 – in Fig. 4, and periodogram of C02 and C04 -– in Fig. 5 with filter transfer functions overlapped.

Scalogram of C02 (Fig. 3) demonstrates bright stripes at 20-year and 60-year periods. The latter are partly masked by the zone of possible edge effects. Scalogram of C04 (Fig. 4) clearly demonstrate annual and semi-annual oscillations in LOD, mainly provided by the atmosphere.
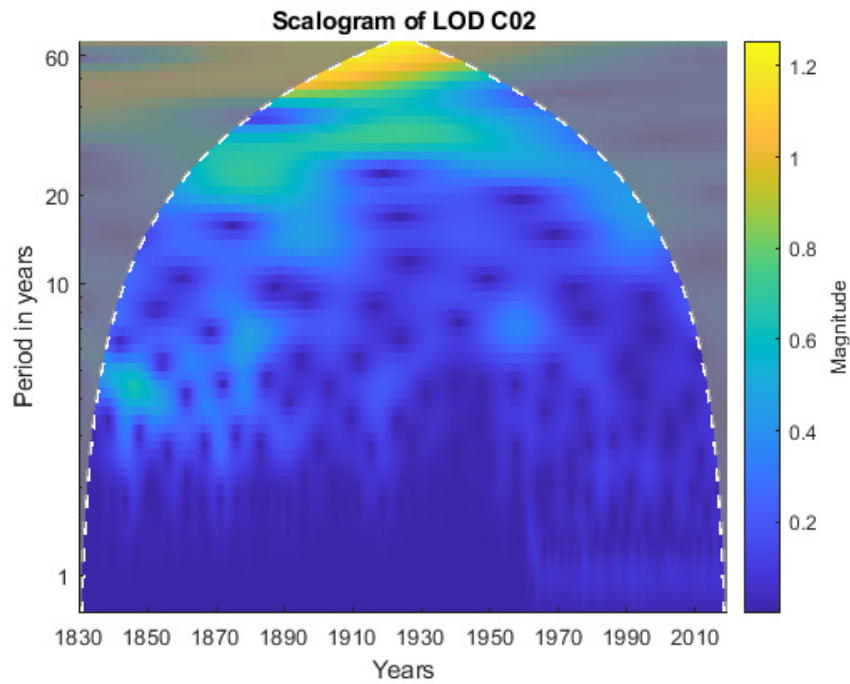
Figure 3. Wavelet-scalogram based on EOP C02. Period in years over ordinate, years since 1830 over abscissa.
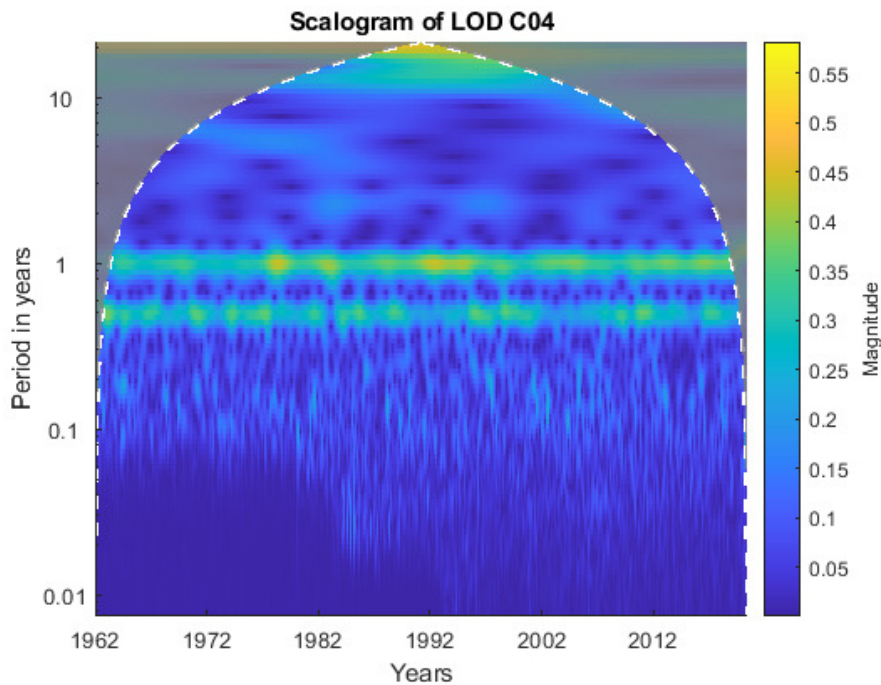

Figure 4. Wavelet-scalogram based on EOP C04 (tides subtracted). Period in years over ordinate, years since 1962 over abscissa.
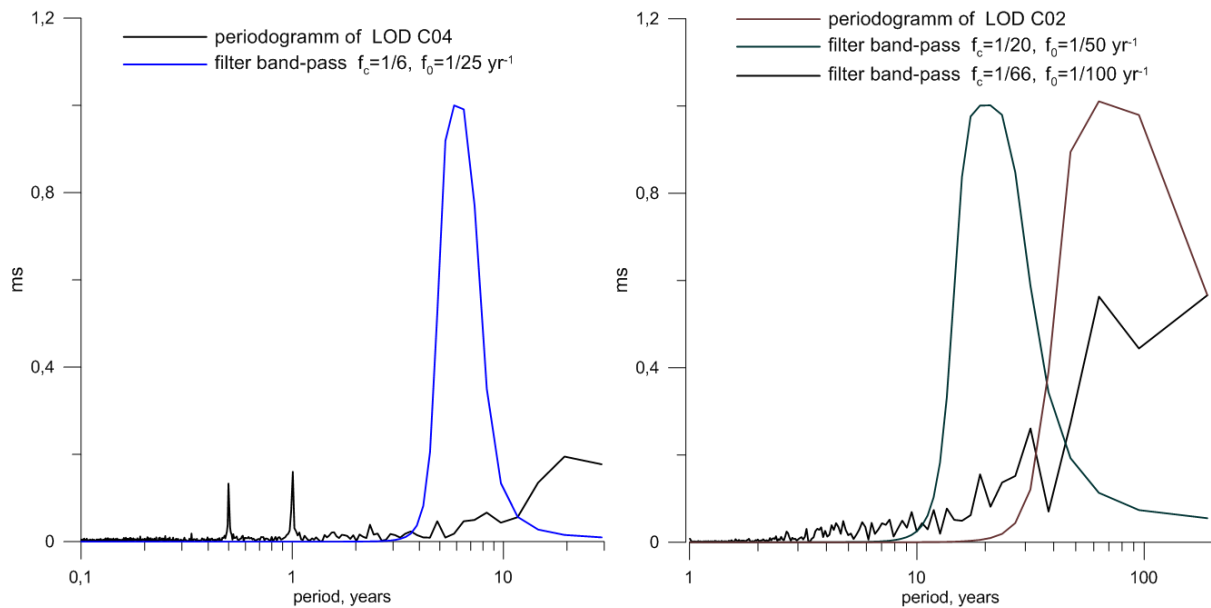
Figure 5. Periodograms of LOD based of EOP C04 (left) and C02 (right) series and corresponding band-passes of Panteleev's filters.

It is well seen how space geodesy, which appeared in 1980, increased the observational precision of high-frequency components of LOD. Periodograms in Fig. 5 based on EOP C04 (left) and C02 (right) series show annual, semi-annual, 2.5-year, 6-year (tiny), 20- and 60-year pikes. We will now extract and investigate 6-year, 20-year and 60-year variations of LOD, make LOD predictions, and then examine the influence of the atmosphere and ocean on LOD.

3. Decadal harmonics adjustment and LOD prediction

To make a prediction of LOD, we will build a simple model refining the periods of 20- and 60-year harmonics with the use of the non-linear method of least squares.
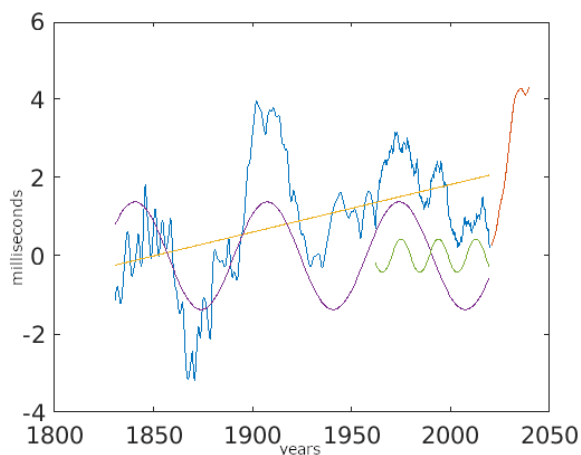

Figure 6. Adjustment for LOD. LOD C02 series in blue, linear trend yellow, 20-year harmonic green, 60-year harmonic purple.
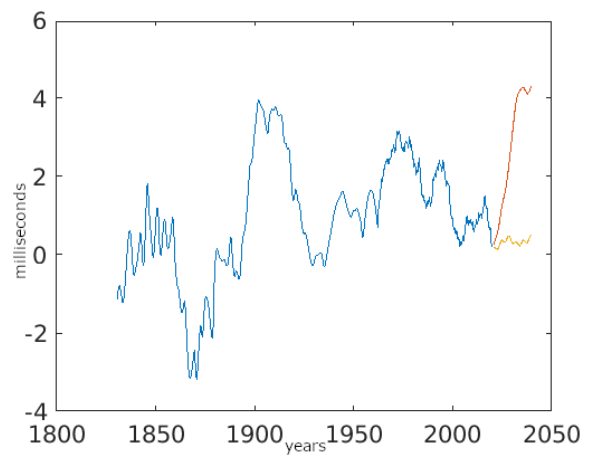
Figure 7. C02 LOD series and its prediction based on above model (orange) and neural network (yellow).

We assume that only EOP C04 LOD data is precise enough to adjust 20-year oscillation. Using EOP C04 bulletin (i.e. since 1962), a 20-year harmonic model was adjusted and is shown in Fig. 6 (in green). The longer terms with larger amplitudes require larger extent of initial data. Using EOP C02 bulletin (i.e. since 1830), a 60-year harmonic was adjusted and is shown in Fig. 6 (in purple). A linear increasing trend (0.012 ms/year) of LOD (Fig. 6, yellow) was also estimated. The periods of 20- and 60-year oscillations refined by the non-linear least squares method were found to be 18.9 and 66 years, respectively. We will continue to refer to them as 20- and 60-year oscillations. It should be noted that at the moment (2020) the obtained 60-year harmonic is rising, and so is the linear trend; but the 20-year harmonic is at its minimum, which implies that in the nearest future LOD will stop decreasing and begin to increase.

We built a forecast for the next 20 years by extrapolating the trend, 20- and 60-year harmonics adjusted above, as well as an autoregressive model of order 10 for the residuals. Such a forecast shown in Fig. 7 (in red) goes up sharply.

We also used the simplest neural network of 15 neurons in 3 layers, trained by 20 preceding EOP C02 points (2000 days) and made a point-by-point prediction of LOD into the future. With this approach, the growth of LOD turned out to be less dramatic (Fig. 7, orange). Nevertheless, both predictions allow to suppose that the Earth's rotation rate will soon stop increasing and will begin to decrease, and LOD will begin to grow.

4. LOD filtering in different frequency bands

4.1. Panteleev's filtering method

Now we will extract the oscillations of our interest with 6-, 20-, 60-year periods using a filter named after the Russian marine gravimetrist V.L. Panteleev. The impulse response of Panteleev's bandpass filter is given by the formula:

$$h(t) = \frac{\omega_0}{2\sqrt{2}} e^{-\left(\frac{\omega_0|t|}{\sqrt{2}} - i2\pi f_c t\right)} \left(\cos\frac{\omega_0 t}{\sqrt{2}} + \sin\frac{\omega_0|t|}{\sqrt{2}}\right), \tag{1}$$

with parameters $\omega_0 = 2\pi f_0$, which determine its width and f_c, which determines the center frequency. The filter transfer function is given by:

$$L_h(f) = \frac{f_0^4}{(f - f_c)^4 + f_0^4} . \tag{2}$$

We will select the filter width f_0 depending on the frequency we would like to extract. With a decrease in the center frequency, the filter will inevitably pass some remaining components of the trend and adjacent low-frequency fluctuations. This could be prevented by reducing the filter bandwidth, which we will do by selecting the width parameters $f_0 = 0.04$, $f_0 = 0.02$ and $f_0 = 0.01$ year^{-1} for 6-, 20- and 60-year harmonics centred at $f_c = 1/6, 1/20, 1/66$ year^{-1}, correspondingly. For the output signal to be valid, we pass spectral components in both the prograde and retrograde frequency bands and add them together. Since the duration of the observation series is limited, and narrowing of the filter $L_h(f)$ in the frequency domain entails an expansion of its time window $h(t)$, the smaller value of f_0 implies the increase of the edge effects region, especially influencing the results of EOP C04 data processing. We will preliminarily remove the effects of zonal tides from EOP C04, but not from EOP C02 series, supposing that the precision of the latter is not high enough to do this. Taking into account possible influence of the atmosphere and the ocean on the LOD, we will filter the angular momenta in the same ranges with the parameters of the filters chosen above.

4.2. 6-year LOD oscillation

To extract 6-year LOD oscillation, we took the filter parameters $f_c = 0.167$, and $f_0 = 0.04$ year^{-1} and used Panteleev's filtering option implemented directly on the EOP PC portal.

The results are shown in Figures 8 and 9, where the signal itself is in red, and its envelope is in blue. The graphs are based on C02 and C04 series respectively. The amplitude is unstable and fluctuates, reaching 0.3 milliseconds.
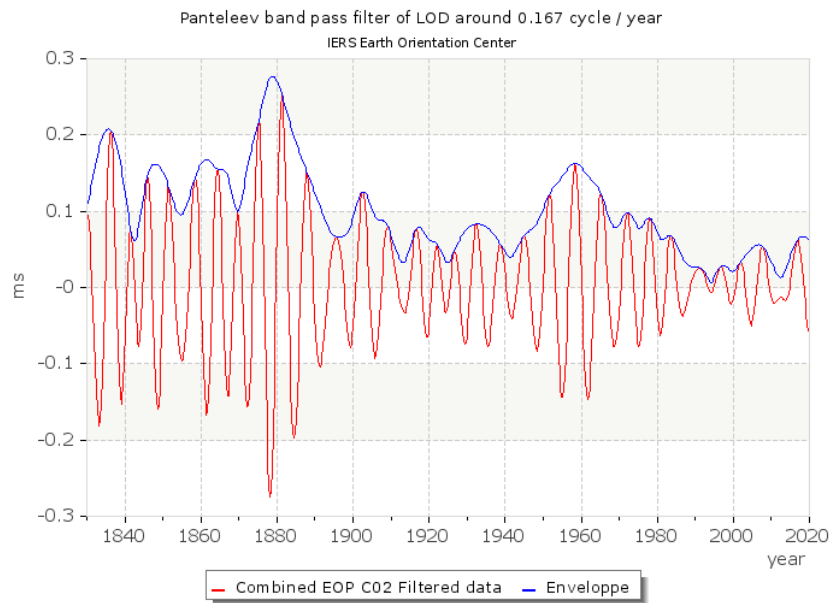

Figure 8. 6-year oscillation of LOD extracted by Panteleev's filter from EOP C02 series (red), and its envelope (blue). In milliseconds.
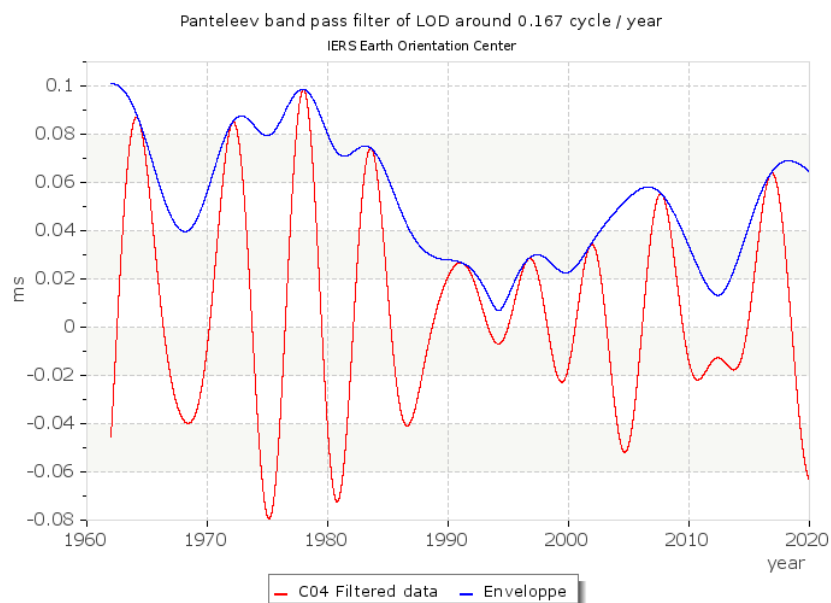

Figure 9. 6-year oscillation of LOD extracted by Panteleev's filter from EOP C04 series (red), and its envelope (blue). In milliseconds.

4.3. 20-year LOD oscillation

Let's consider a 20-year LOD signal (more precisely, an 18.9-year signal) by fixing $f_c = 0.053$ year^{-1}. We performed filtering with several different filter width parameters f_0, results are presented in Fig. 10, left. Secular signals can propagate to the filtered signal in case of large f_0 parameter, thus, the closer f_c is to zero, the smaller f_0 is preferable. The payment for this is widening of the edge effects, because time-window $h(t)$ becomes larger according to the Heisenberg uncertainty principle. Therefore, we selected $f_0 = 0.02$ year^{-1} for 20-year oscillation.
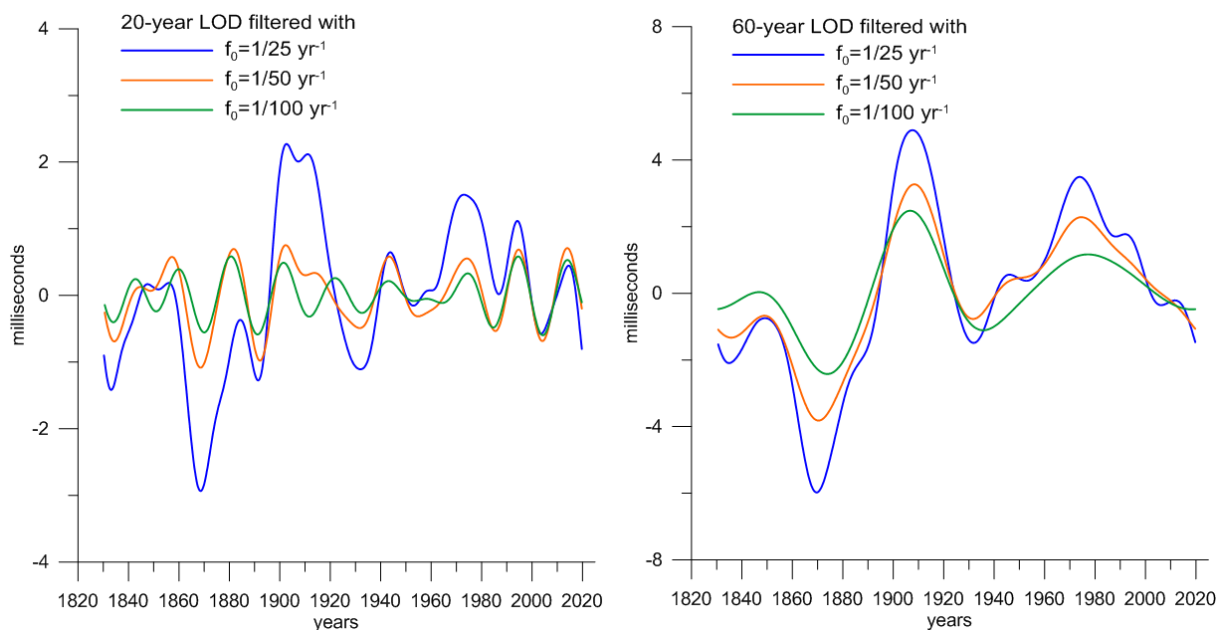

Figure 10. Comparison of 20-year (left) and 60-year (right) components for different filter widths for EOP C02 LOD series.

Figure 11, left, shows 20-year oscillation from EOP CO2 (blue) and C04 data (red). There is decent agreement between them, yet it slightly worsens at the right edge, apparently due to edge effects, which can distort the signal within tens of years. It is clearly seen that the amplitude of the oscillation is not constant, reaching 1 millisecond.

4.4. 60-year LOD oscillation

For a 60-year LOD signal filtering, the value $f_c = 0.015$ cycles per year was chosen as the centre frequency, which corresponds to 66-year period. As mentioned above and from comparison of results for different values of width parameter f_c shown in fig. 10, right, we selected the width parameter $f_0 = 0.01$ cycles per year here.

Figure 11, right, shows the graph of the 60-year LOD fluctuation filtered out from C02 bulletin data since 1830 (in blue) and C04 data since 1962 (in red). The agreement between them, considering the edge effects, is acceptable, and the signal amplitude reaches 3 milliseconds.

5. Analysis of oceanic and atmospheric contribution

Over the past half-century, it has been established that the exchange of the angular momentum between the atmosphere, the ocean and the solid Earth is one of the main causes of variations in the Earth's rotation rate [2]. In order to understand whether the oscillations extracted above
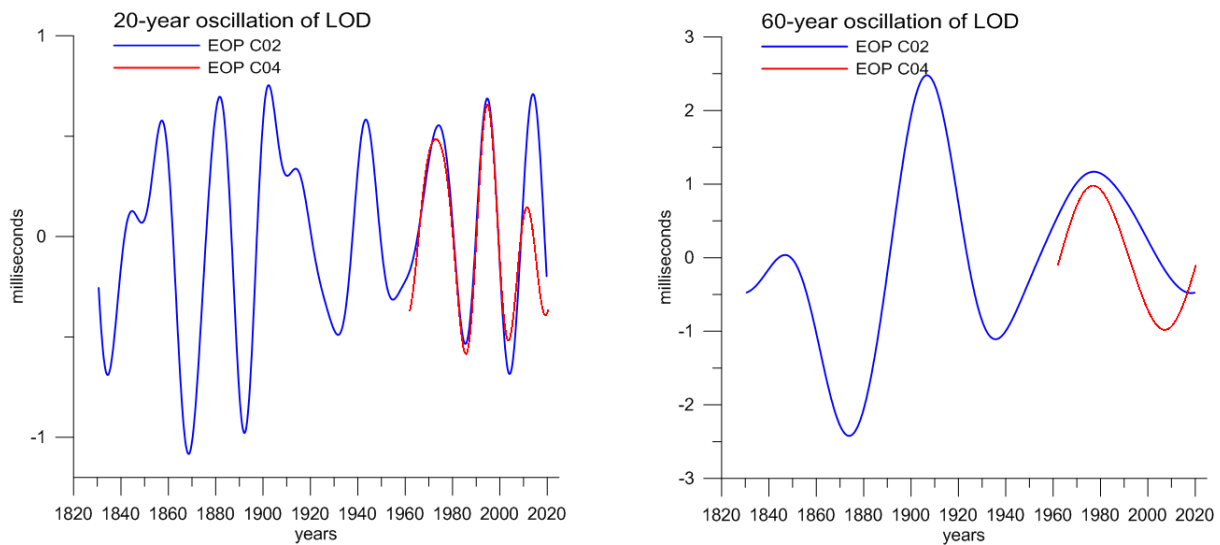
Figure 11. 20-year (left) and 60-year (right) oscillations in LOD extracted by Panteleev's method from C02 (blue) and C04 (red) series.

are caused by the influence of the ocean and the atmosphere, we will analyse the impact of the axial components of the angular momentum functions of the atmosphere (AAM) and the ocean (OAM) on the LOD changes in the selected frequency bands.

5.1. OAM analysis

The Oceanic Angular Momentum OAM series are analysed according to the data from two centres: GFZ [18] (Helmholtz Potsdam Center for Earth Sciences) and ECCO [19] ("Estimating the Circulation and Climate of the Ocean" consortium). We consider only the axial z-component, which influences the Earth's rotation rate. With the use of Panteleev's filter, we filter out the corresponding data series in the bands corresponding to 6-, 20- and 60- year periods with parameters values, chosen above (see also Fig. 5).

Figure 12, left, shows the 6-year component of the ocean angular momentum (OAM) extracted by Panteleev's filter, according to ECCO (since 1949) and GFZ (since 1976) data. The amplitude of this ocean influence (several microseconds) on LOD in the 6-year range is insignificant in comparison with the extracted 6-year LOD signal itself.

Figure 13, left shows the OAM signal filtered in the same way in the 20-year range according to the data from GFZ and ECCO. OAM data obtained from contemporary reanalysis centres are non-durable and may account for long-term processes not very precisely. Besides, the results of filtering are under influence of edge effects. Nevertheless, the 20-year OAM signal amplitude is extremely small: at the level of 10 microseconds.

Figure 13, right, shows the 60-year component of the ocean angular momentum (OAM) extracted by Panteleev's filter according to the data from ECCO and GFZ. The oscillation amplitude is within 5 microseconds. Despite the fact that with an increase of oscillation periods (from 6 to 20 to 60 years) the amplitude of the OAM signal increases, we believe that it is possible to disregard the oceanic contribution to long-term LOD variability due to the extremely small final amplitudes.
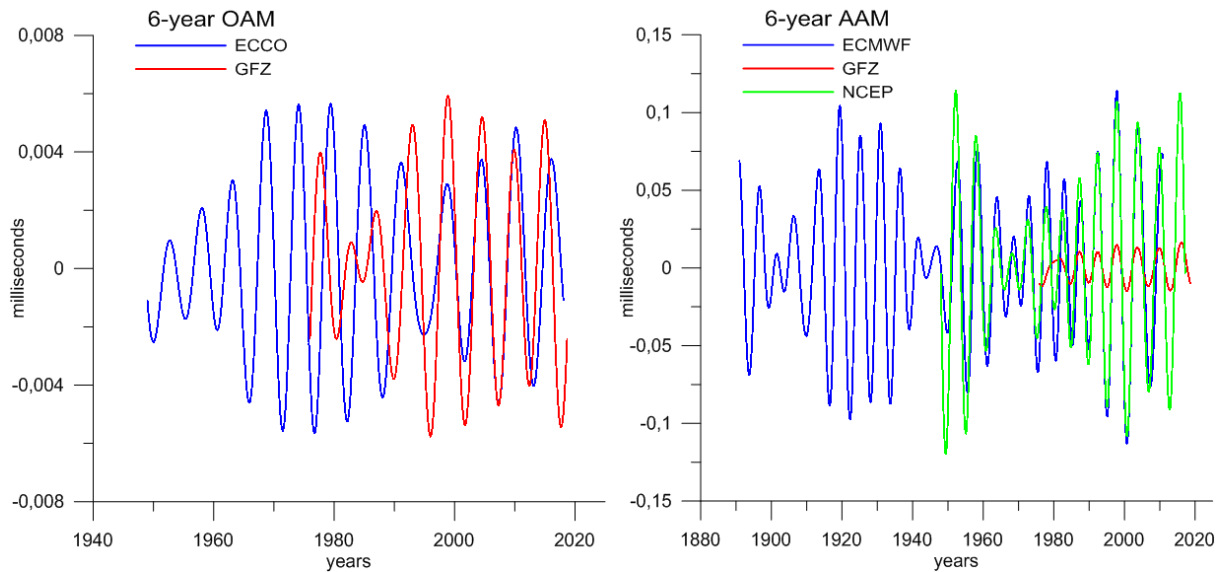
Figure 12. Left: 6-year OAM component extracted by Panteleev's filter from GFZ (green) and ECCO (blue) series. Right: 6-year AAM component extracted by Panteleev's filter from GFZ (red), NCEP (green) and ECMWF (blue) series.
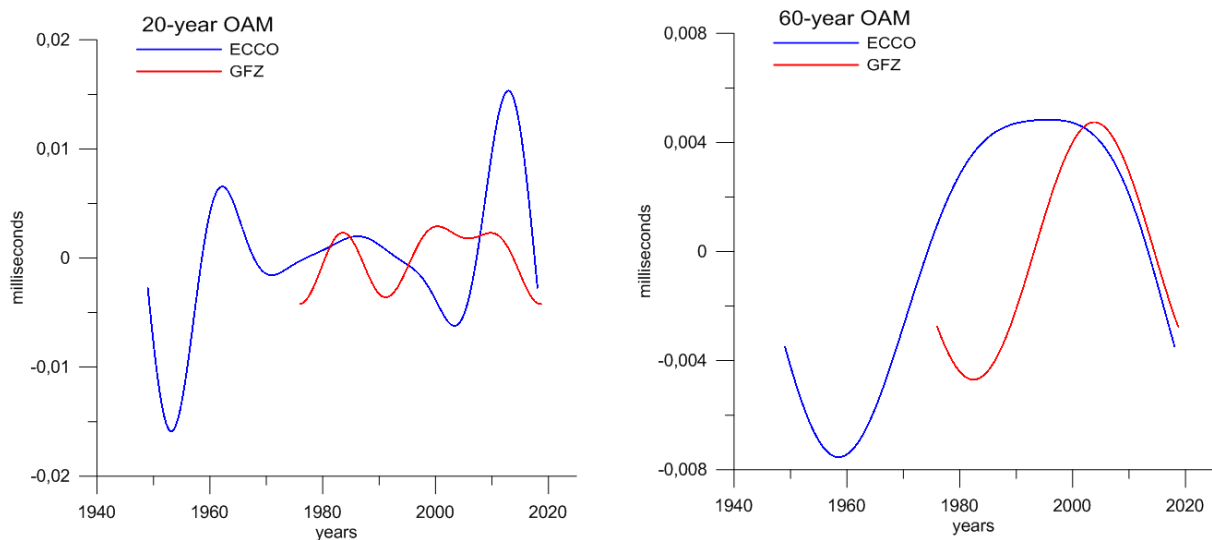

Figure 13. 20-year (left) and 60-year (right) OAM component extracted by Panteleev's filter from GFZ (green) and ECCO (blue) series.

5.2. AAM analysis

For AAM analysis, the data from three centres – NCEP [20] (National Centers for Environmental Prediction of the USA), ECMWF [21] (European Center for Medium-Range Weather Forecasts) and GFZ – were analysed. The reanalysis of the atmosphere carried out by these centres allows to collect the data on the global angular momentum AAM over the following time intervals: since 1900 – ECMWF, since 1949 – NCEP and since 1977 – GFZ.

Figure 12, right, shows the 6-year components of the atmospheric angular momentum (AAM) series filtered by Panteleev's filter according to the data from NCEP, ECMWF, and GFZ. We

do not have explanation, why the latter has smaller amplitude than the others.
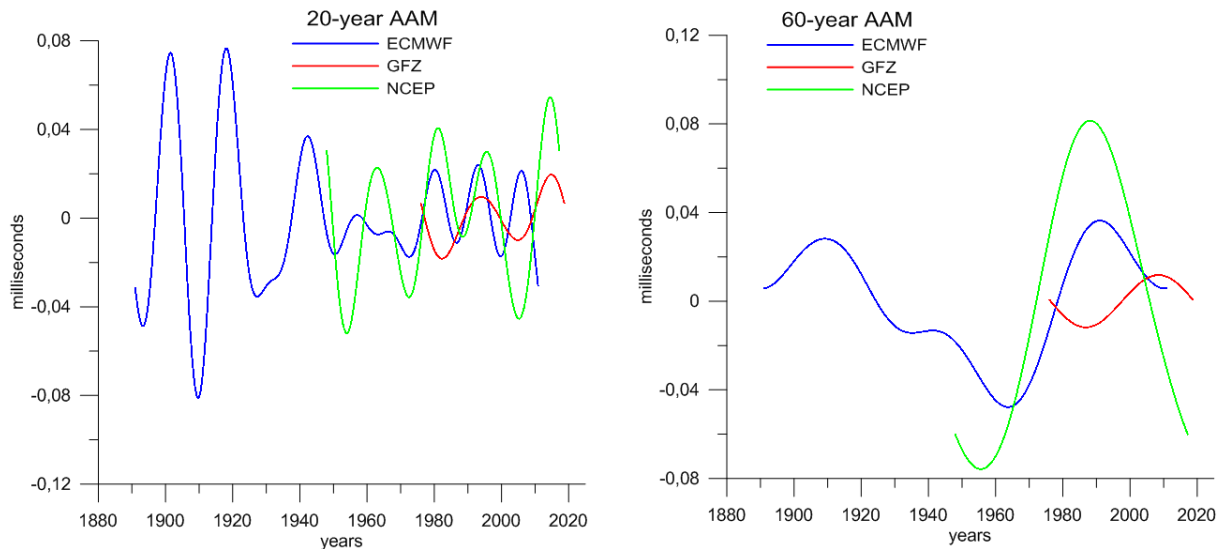

Figure 14. 20-year (left) and 60-year (right) AAM component extracted by Panteleev's filter from GFZ (red), NCEP (green) and ECMWF (blue) series.

Figure 14, left, shows the graphs of 20-year oscillations of the axial AAM filtered by Panteleev's filter. As seen from Figure their amplitude is not constant, it fluctuates within 0.08 millisecond. While the fluctuations in the AAM ECMWF and NCEP data are more or less similar, the GFZ data starting in 1977 is too short and, most likely, is distorted by the edge effect. The question of minimizing of their influence was raised in the report [11], but is beyond the scope of this work.

Figure 14, right, shows the filtered 60-year AAM from NCEP, ECMWF, and GFZ data. The amplitude reaches 0.1 milliseconds, but still is tens of times less than the LOD signal in this frequency band.

5.3. Accounting for the influence of OAM and AAM on LOD
The influence of the ocean on the Earth's rotation rate (and the length of the day, LOD) is less significant than the influence of the atmosphere. This is due to the fact that the atmosphere is more mobile than the ocean, and its zonal flow is not limited by continents, in contrast to currents in the ocean.

Figure 15 shows the filtered 6-year LOD signal after subtracting AAM from it. We did not subtract the 6-year OAM contribution, since it is very insignificant in amplitude. It is worth noting that the 6-year oscillation freed from the atmospheric influence became more stable, which confirms the results obtained by Hao Ding [5], and refutes the assumption about the continuous damping of the 6-year oscillation since 1962, made in [6]. A study of 6-year fluctuations was also carried out in [14, 15].

Considering the contribution of the ocean and the atmosphere to the multidecadal variations of LOD, from the comparison of the 60- and 20-year fluctuations of AAM and OAM with the amplitude of the corresponding LOD variations, we concluded that they did not influence multidecadal LOD significantly; thus, we did not subtract AAM and OAM from LOD fluctuations in these bands. However, this does not diminish the importance of studying the long-term components in the series of the corresponding angular momenta. Therefore, it seems that the exchange of angular momentum between the atmosphere, the ocean and the solid
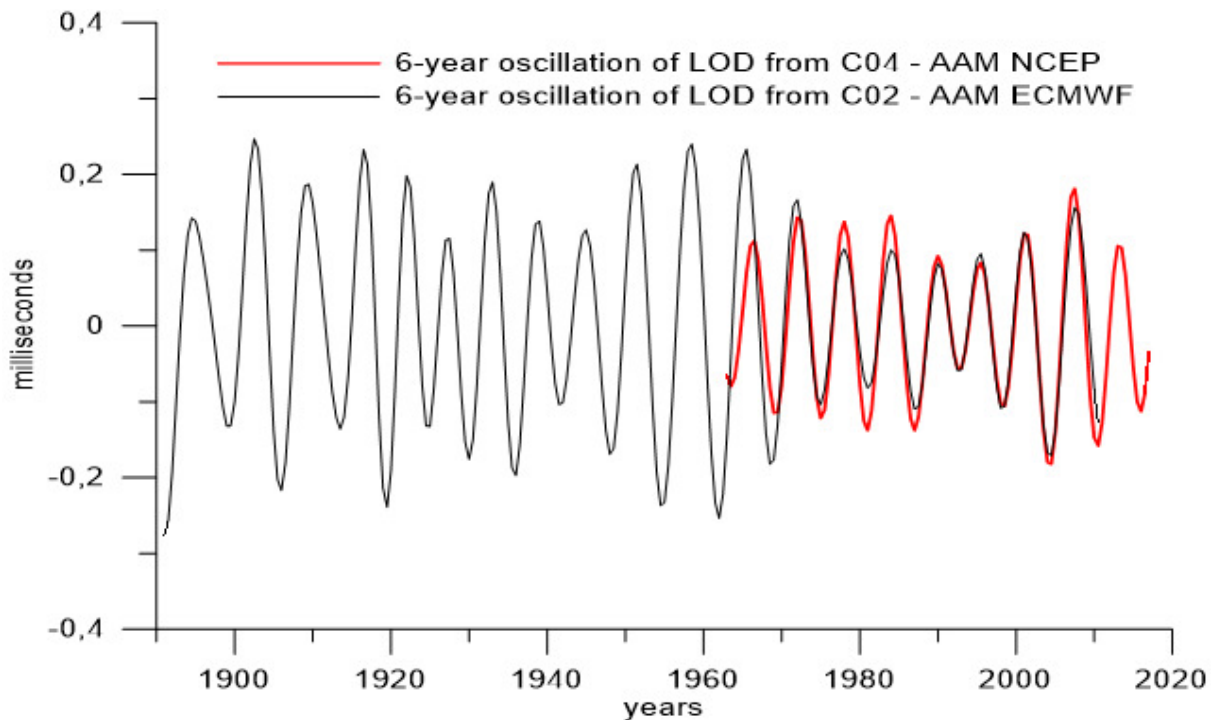
Figure 15. Final 6-year component of LOD after subtraction of AAM from C02 (black) and C04 (red) series.

Earth, which perfectly explains the annual and interannual non-tidal fluctuations in LOD, cannot explain the long-term features in LOD. For example, in Fig. 16 from EOP PC portal it can be seen that after the El Nino phenomenon, which slowed down the Earth in 2016, the speed of its rotation began to grow (and LOD began to decrease), which is only partly explained by the influence of oceanic and atmospheric angular momenta.

What causes the decadal changes is of great interest. Are they really related to the processes in the Earth's interior? While the 6-year fluctuations in LOD are theoretically associated with eigen oscillations of the core, such explanation does not exist for the 20 and 60-year fluctuations. Therefore, they should be forced by some factor. In the next section, we will try to look at some other geophysical processes that may be associated with LOD variability.

6. Comparison of multidecadal oscillation of LOD with global Earth's temperature, sea level, magnetic field anomalies and Chandler wobble

In recent decades the problem of climate changes has become highly actual. The major characteristics of these changes are global temperature and sea level rise, depicted in Fig. 17 for the latest one and a half century. The temperature plot on the left is based on HadCRUT 4 time series, Sea Level – on reconstruction of S. Jevrejeva [7], merged with satellite altimetry since 1993. The average speed of temperature rise is around 0.7 degree per century, of sea level rise – 3 mm per year.

After the trend adjustment (parabolic for temperature and linear for sea level) and its subtraction, the anomalies were obtained and depicted in Fig. 18. Both plots have prominent 60-year variations. To make this better seen, we smoothed the signals with low-pass ($f_c = 0$) Panteleev's filter with parameter $f_0 = 0.1$ cycles per year and plotted results in black. Such filtering allows to pass both 60 and 20-year periods. Both variations in temperature and sea
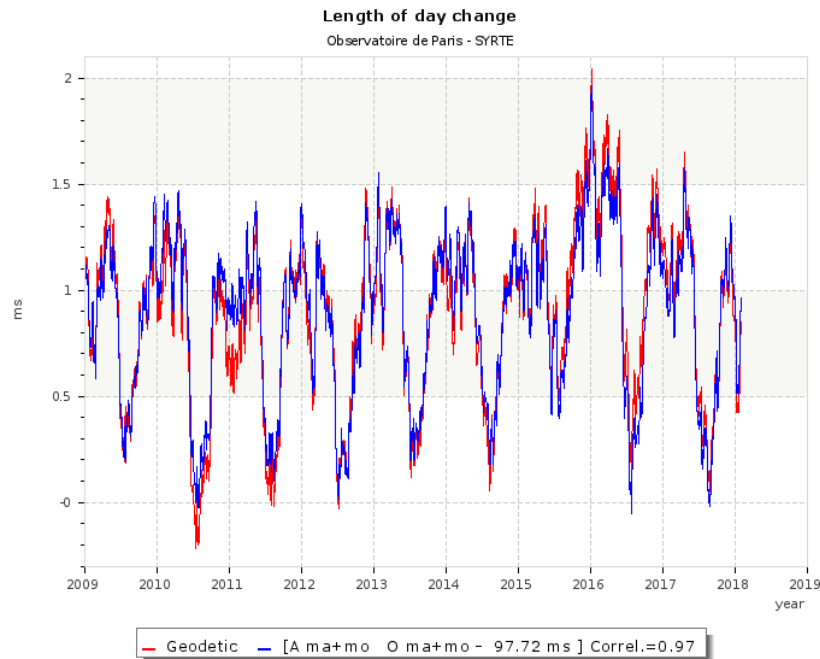
Figure 16. Comparison of LOD (geodetic, red) with the sum of OAM and AAM contributions (geophysical, blue) in the interannual band from EOP PC site.
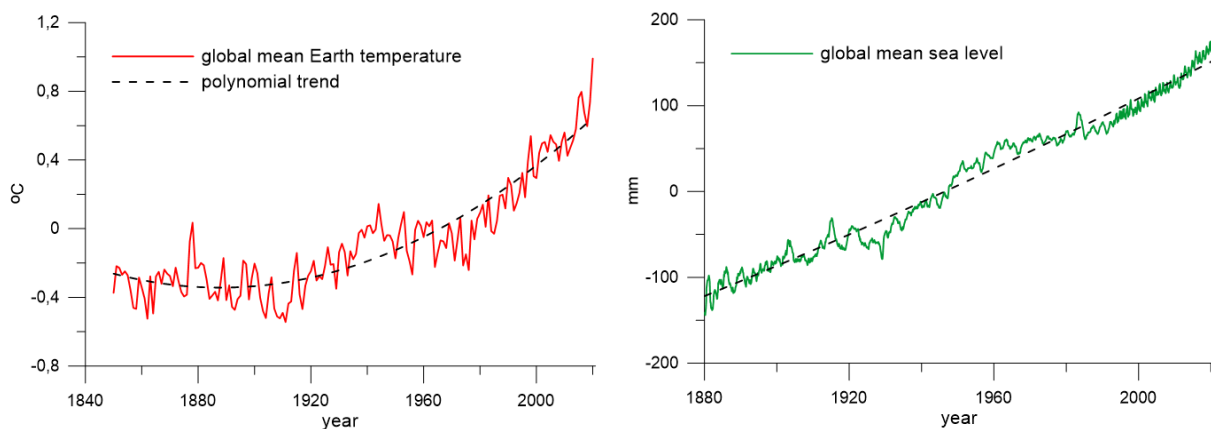

Figure 17. Global mean Earth temperature (left) and global mean sea level changes (right).

level can be also extracted by Multichannel Singular Spectrum Analysis (MSSA) [12]. But in present work we show them extracted by Panteleev's filtering.

20-year anomalies of temperature and sea level, extracted by Panteleev's filter with parameters $f_c = 1/20$, $f_0 = 0.02$ year^{-1} are represented in Fig. 19 together with 20-year inverted LOD variations from EOP C02 bulletin (representing Earth's rotation velocity). The total correlations with LOD are not very high (around 0.1). But correlation between 20-year components of temperature and sea level is 0.45. After 1962 mutual correlations increase. Supposing the predictions of Section 3 are correct, if LOD grows, temperature oscillation will go down.

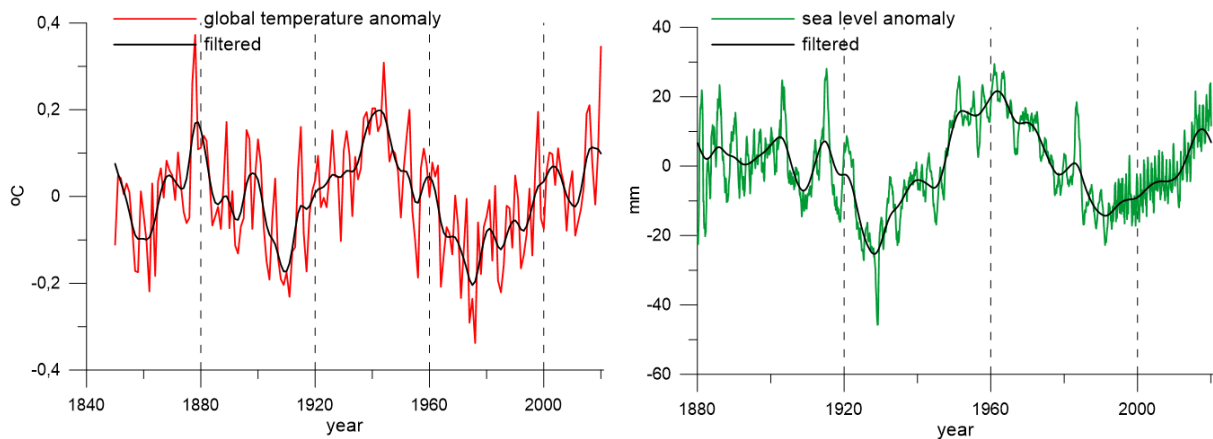Comparison of 60-year variations, extracted by filtering with parameters $f_c = 1/66$, $f_0 = 0.01$

Figure 18. Global Earth's temperature anomaly (left). Mean sea level anomaly (right).

year^{-1}, with inverted LOD signal is done in Fig. 20. The correlation of Earth's rotation velocity (-LOD) and temperature anomaly is high (0.85). Other correlations between 60-year components are around 0.2. But it is seen that sea level anomaly is phase delayed with respect to them.
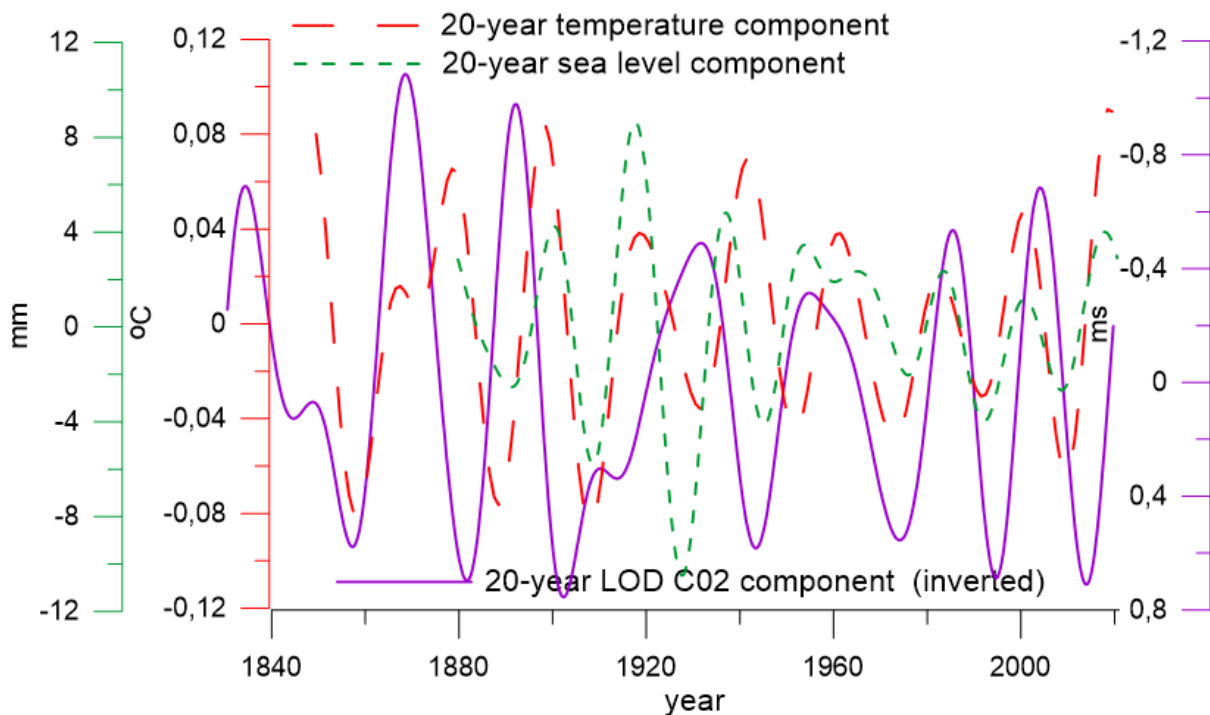

Figure 19. Comparison of anomalies in global temperature, sea level and 20-year LOD variations.

Next, we compared 60-year LOD changes with Chandler wobble amplitude (envelope) (Fig. 21, left), and 20-year LOD – with Chandler excitation envelope (Fig. 21, right). Chandler wobble itself demonstrates quasi-60-year amplitude variations, its excitation shows quasi-20-year beatings [13, 12]. If LOD variations are found to reflex amplitude modulations of the Chandler wobble, then it would require a revision of the theory, which now treats this effects as
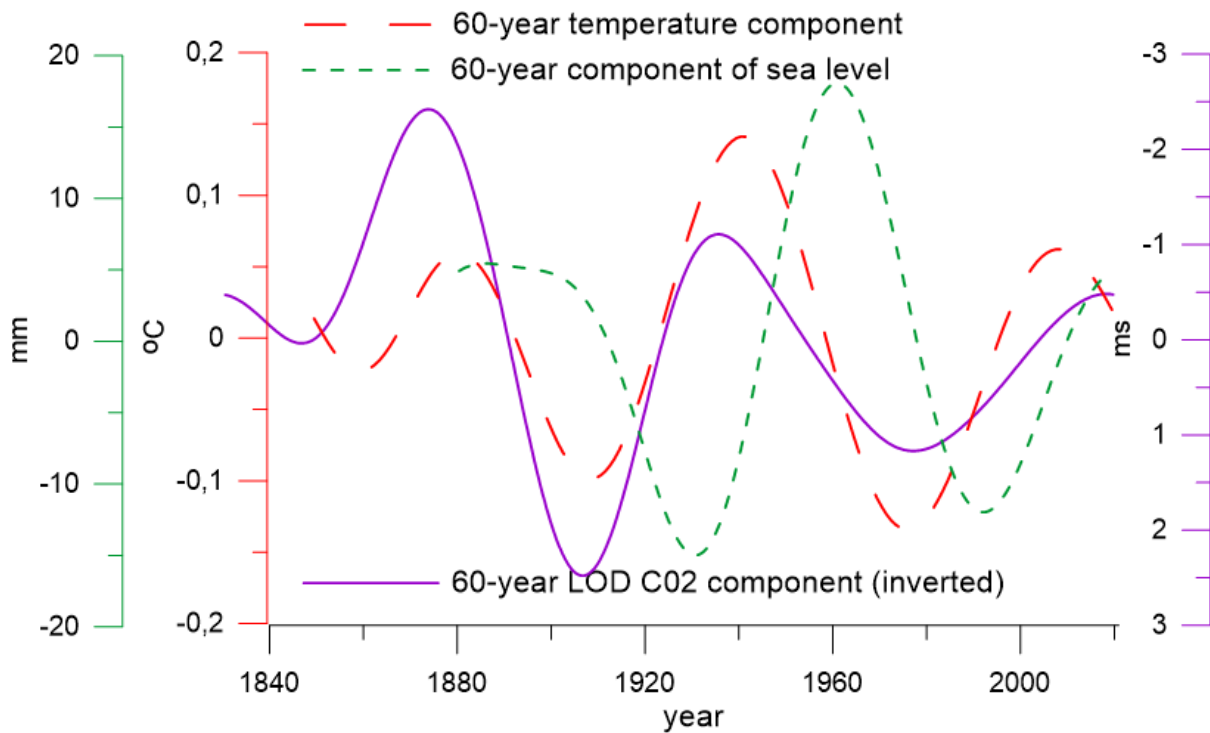
Figure 20. Comparison of 60-year variations in global temperature, sea level and LOD.
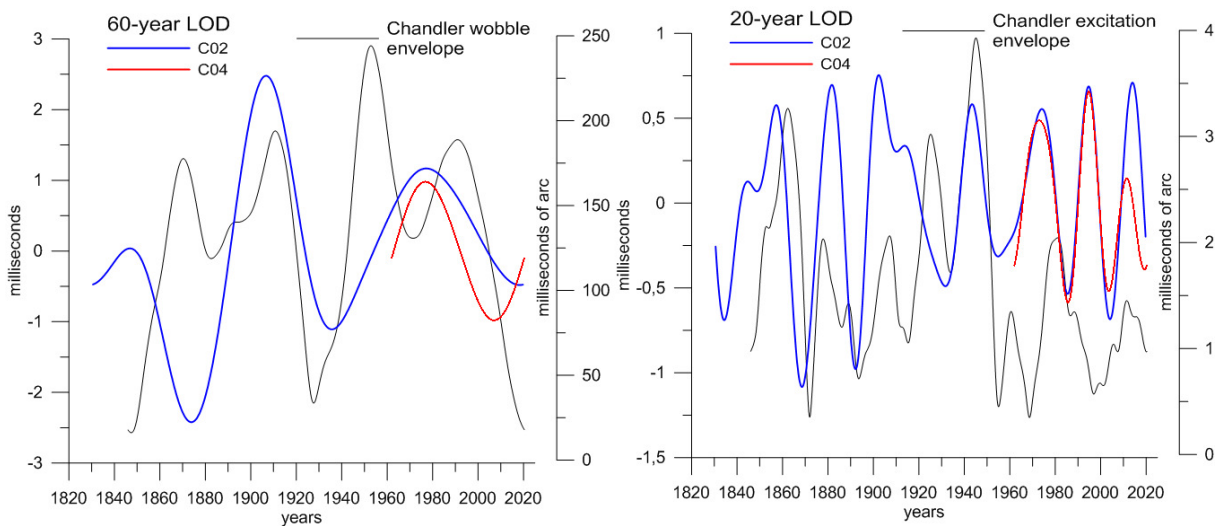
of the second order.

Figure 21. Comparison of the Chandler wobble envelope with 60-year LOD (C02 and C04) variations, left, and of the Chandler excitation envelope with 20-year LOD variations, right.

Finally, in Fig. 22 we compare 60-year LOD with the Earth's magnetic dipole strength (detrended). Their agreement is quite evident, which makes the hypothesis of the relation of 60-year changes in Earth's rotation with the processes in the Earth's interior quite plausible.
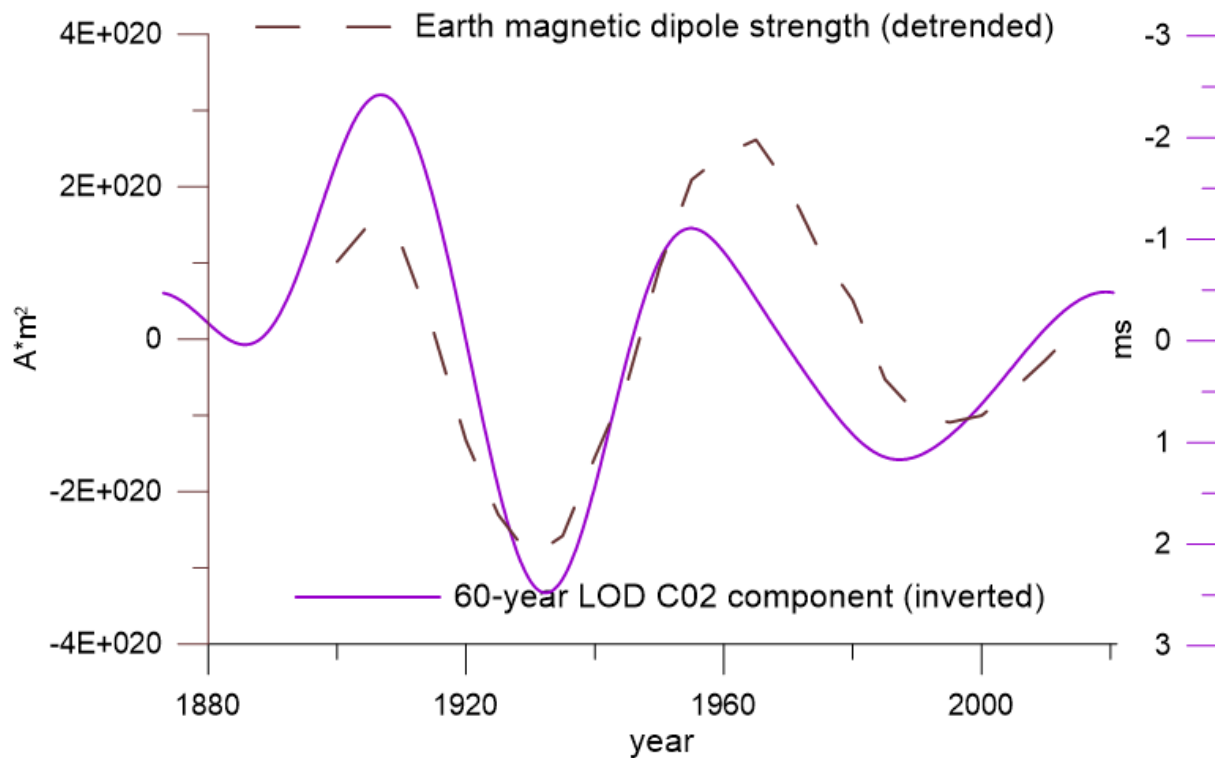
Figure 22. Comparison of the anomalies of the Earth magnetic field dipole and 60-year LOD variations.

7. Conclusion

In presented study we filtered out and analysed 6-, 20- and 60- year oscillations in LOD; the two latter periods were more accurately estimated as 18.9 (from C04) and 66 (from C02) years. The influence of the atmosphere and the ocean was estimated. It was found out that the oceanic input at 6-, 20- and 60-year periods is negligibly small, as well as the atmospheric influence at 20- and 60-year periods (at least what can be obtained from the angular momentum functions analysis). After atmospheric input subtraction, 6-year oscillation became more prominent and stable, which proves the results of Hao Ding [5], but contradicts the assumption given in [6] about the decay of this oscillation since 1962. The 20- and 60-year oscillations were compared with the anomalies of global Earth temperature, sea level, strength of magnetic dipole and Chandler wobble. We found out that 20-year oscillations in temperature and sea level often repeat the changes of the Earth's rotation velocity, especially since mid-XX century; 60-year oscillation in temperature is well correlated with the inverted LOD. The comparison of LOD with anomalies of the Earth's magnetic dipole intensity supports the hypothesis about the relationship of the processes in Earth's interior with the 60-year Earth's rotation velocity changes. Such correlations can help to predict this velocity, which has been rising since 2016 up until now (2020), together with climatic signals. The prediction built for the next 20 years based on the simple model (described in Section 3) makes us expect the Earth's rotation velocity to stop growing soon and start decreasing, therefore, causing LOD to grow.

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