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Manifestation of Solar and Geodynamic Activity in the Dynamics of the Earth's Rotation

V. L. Gorshkov, N. O. Miller, and M. V. Vorotkov

Central Astronomical Observatory, Russian Academy of Sciences, Pulkovo, St.Petersburg, Russia

e-mail: vigor@gao.spb.ru

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Abstract—The relationships between different manifestations of solar and geomagnetic activity and the structural peculiarities of the dynamics of the pole wobble and irregularities in the Earth's rotation are studied using singular spectrum analysis. There are two close major peaks and several lower ones in the same frequency range (1.1–1.3 years) in the Chandler wobble (CW) spectrum. Components in the geomagnetic activity were distinguished in the same frequency band (by the Dst and Ap indices). Six- to seven-year oscillations in the Earth's rotation rate with a complex dynamics of amplitude variations are shown in variations in geomagnetic activity. It is revealed that secular (decade) variations in the Earth's rotation rate on average repeat global variations in the secular trend of the Earth's geomagnetic field with a delay of eight years during the whole observation period.

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1. INTRODUCTION

The causes of low-frequency decade and secular variations in geophysical processes are difficult to interpret because monitoring instruments have only been available for a short period of time (200–300 years). At the same time, their significance permanently increases both in terms of scientific and applied (prognostic for climate changes) aspects.

Low-frequency interannual variations are also present in the Earth's rotation dynamics, represented by the series of the Earth's rotation parameters (ERP), such as the pole coordinates {Xp,Yp} and variations in the Earth's rotation rate (variations in the length of the day ΔLOD = 86400 – LOD s). These variations are of a complex irregular nature, which reflects the interaction of the lithosphere, where all instruments for ERP monitoring are located, with geophysical processes mainly in the Earth's fluid layers and in the liquid core. The geophysical functions of the atmospheric (AAM), ocean (OAM), hydrosphere (HAM), and inner core angular momenta (CAM) are calculated using corresponding (mainly model) data.

Thus, if one solves the inverse problem, then variations in the Earth's rotation vector can serve as an indicator of these processes. At the same time, the dynamics of geophysical processes is supported by the influence of solar activity and the activity of the Earth's interior (core and mantle), including the Earth's geomagnetic activity.

Two groups of hypotheses try to explain the causes of the appearance of long-term variations in the Earth's rotation dynamics. Hypotheses about the excitation of ERP variations by electromagnetic and gravitational interactions at the core–mantle boundary are the most popular (Holme, 1998; Dumberry and Bloxham, 2002; Spiridonov and Yakimenko, 2003). However, to build an adequate theory, the available data on the model parameters are insufficient; therefore, estimation of the possible effect of angular momenta, which appear at this boundary and are recorded in the form of geomagnetic variations, is used more often (Hide et al., 2000; Bellanger et al., 2002). The second group of hypotheses assumes that the Sun is a source of excitation (Djurovič and Pâquet, 1996; Abarca del Rio et al., 2003). Statistical relationships between the index of solar and geomagnetic activity and variations in the Earth rotation rate (ΔLOD) or variations in the CW amplitude are mainly considered in these works.

In this work, variations in the LOD and CW amplitudes are studied using the multidimentional singular spectrum analysis (MSSA) method along with solar and geomagnetic indices. This method allows us to reveal the general structure in a set of jointly studied series with an assumed interdependence. The method has good frequency and time resolutions, which allows one to develop a new approach to the joint analysis of a large volume of dissimilar data.

Only interannual and secular variations in the Earth's rotation vector are studied in this work, along with solar activity, among the whole variety of variations, and only those, the nature of which is unclear, including decade variations in the Earth's rotation rate, with periods of 40–70 years and amplitudes of 3–4 ms and 5–7-year variations with amplitudes up to 0.3 ms. The excitation of 2- to 3-year variations in

LOD is satisfactorily explained by AAM, while the excitation of 5- to 7-year variations remains hypothetical (Gorshkov, 2010). The CW with a period of 428–435 days is the most questionable in the pole wobble in view of both excitation and amplitude modulation.

2. DATA

Data on the solar and geomagnetic indices were taken from the Geophysical Data Center in Boulder (ftp.ngdc.noaa.gov/STP/SOLAR_DATA/). We used data on the radio flux at an F10.7-cm wavelength (beginning from 1947), the FI flare activity index (from 1966), and the Ap (1932–2010) and Dst (1957–2008) geomagnetic indices. These data have been reduced to an equal time interval of 0.05 year. Monthly average series of areas (SSAr) and sunspot numbers (SSN) in 1750–2010 were taken from (Nagovitsyn, 2005). The composite series ACRIM(1,2,3)–Nimbus7 of total solar irradiance (TSI) for 1978–2010, described in (Wilson and Mordvinov, 2003), were used after 27-day moving averaging with a further interpolation to 0.05 year.

Annual average geomagnetic data (X, Y, Z) for 1843–2010 were taken from the World Data Center (ftp.nmh.ac.uk/wdc/obsdata/) in Edinburgh. Monthly INTERMAGNET geomagnetic data (Chulliat and Telali, 2007) for 1883–2007 were also used for comparison. Observatory data were used for calculations of secular variations in the Earth's magnetic field (SV_N, SV_E, SV_U).

ERP series C01 from 1846, C04 from 1962, AICAS for 1956–1992, and LUNAR97 for 1832–1997 were taken from the data of the International Earth Rotation Service (http://hpiers.obspm.fr/eop-pc/), as well as the functions of the atmospheric (AAM, NCEP/NCAR reanalysis, 1948–2009) and ocean (OAM, ECCO_50y, 1949–2002) angular momenta. To increase the length of the ERP series, their combinations after valid procedures of their conjunction were also used. In particular, the AICAS series extended by the C04 series is designated in the work as eopAO. All known tidal variations from 5 days to 18 years were removed from the ΔLOD series. It should be kept in mind that an increase in the length of the day corresponds to a decrease in the Earth's rotation rate.

Since data on the AAM and OAM momenta exciting the Earth's rotational dynamics are available starting from the second half of the 20th century, the geophysical excitation reduction of ERPs is also possible beginning from this time only. Therefore, ΔLOD was studied separately for the data after 1956 with an interannual resolution of 0.05 years and geophysical reduction; for all available data, with one-year resolution without taking into account the above-mentioned reduction. A sum of "mass" terms, taking into account the inverse barometer, which is responsible for changes in the moment of inertia, and "motion" terms, originated due to ocean currents and air mass travel, was used in the angular momenta.

3. MAIN RESEARCH METHOD

To study the series, the method of singular spectrum analysis (SSA) and its multivariate version for the joint study of the series (MSSA) from (Golyandina et al., 2001) were used. SSA relates to the class of intrinsic (empirical) orthogonal functions, for which basic decomposition functions are determined from initial data.

MSSA analyzes data sets jointly, distinguishing the general regularities or revealing special features. Using this method, we can obtain the components of different series, which are similar in frequency, and estimate their significance during decomposition. This method is based on the transformation of a time series into a matrix using parameter M (the specified window length) and singular decomposition of the matrix, which results in the additive decomposition of the initial series. The eigenvalues of correlation matrix λ_i are the sampling variances of the corresponding main components, which are ranged so that the first one has the maximum contribution to the total variance. The percentage of the contribution of the i-th component is calculated by the formula $V_i = \lambda_i / M \times 100\%$, where λ_i is the i-th eigenvalue. All series were standardized before using MSSA by $(x_i - x_m)/s$ where x_m and s are the mathematical expectation and standard variation of the $\{x_i\}$ series.

The series were studied jointly using MSSA. However, to determine the spectral compositions of each series, except for the pole coordinates {Xp,Yp}, the SSA method was used. Using this method, we can obtain the components of different series, which are similar in frequency, and estimate their significance during decomposition. When using MSSA, we should take into account how significant (in view of the contribution and amplitude) are the obtained components. Only equivalent components, distinguished at a certain frequency, can be considered interdependent. Therefore series standardization is particularly advised when using MSSA.

4. SSA DECOMPOSITION OF THE STUDIED SERIES

4.1. CW and Geophysical Excitation Functions

There are two close peaks with maximal amplitudes and several small bursts in the same frequency range in the CW spectrum. Six components have been obtained at the CW frequency. The main CW component is the sum of the first two components (with a period of 1.183 years), which makes 40%, and the other four components make 7% (Fig. 1, left-hand side). The weak component consists of a sum of five components with periods of 1.16, 1.21, 1.22, and 1.24 years.

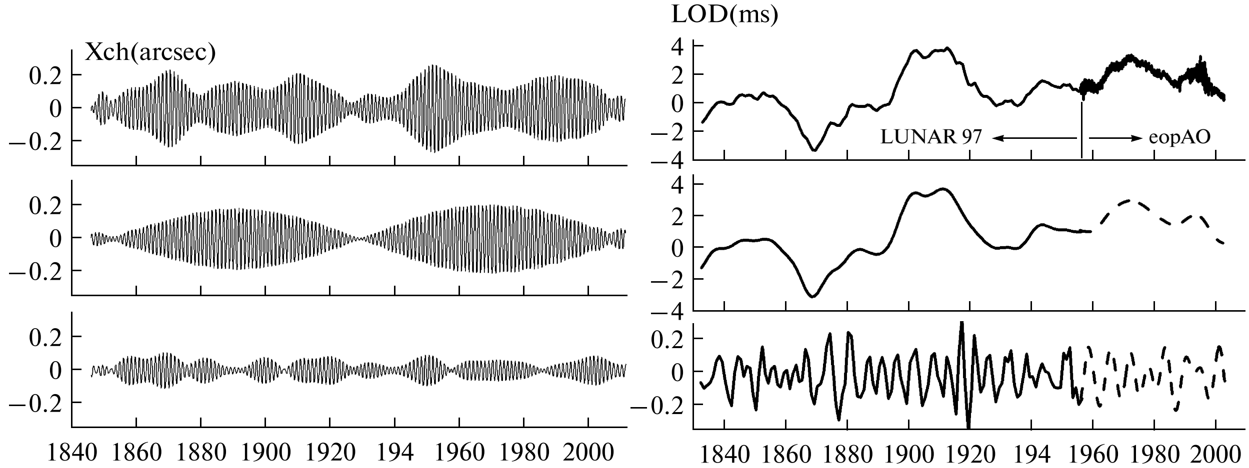

Fig. 1. SSA decomposition of the *X* CW coordinate (left part): (top) total CW, (center) sum of the main components (40%), (bottom) sum of weak components (7%); SSA decomposition of ΔLOD series (right part): (top) composition of ΔLOD series (eopAO series corrected for AAM and OAM), (center) decadal variations in LOD, (bottom) 5- to 7-year variations in LOD.

The main components have about 80-year modulation with intervals of a strong amplitude damping and a simultaneous phase change by about 180°. The first minimum is at the very beginning of the series (around 1853), the second well-known minimum is around 1928, and a sharp damping in the CW amplitude is observed at the end of the series (around 2005). The CW behavior is described in more detail in (Malkin and Miller, 2010; Miller, 2011). In addition, an about 40-year period of amplitude variations can be noted. This regularity was first noted in (Kostina and Sakharov, 1985); the authors connected it with the effect of solar activity. Weak components cause additional decade CW amplitude modulations. The nature of the excitation of these variations in the amplitude and sharp changes in the CW phase cannot be completely explained (like the nature of the CW excitation).

The seasonal components (1 and 0.5 years), which constitute 34 and 29%, respectively, are the main ones in the χ_2 and χ_2 angular momentum functions (AAM and OAM).

4.2. *ΔLOD and Geophysical Excitation Functions*

Figure 1 (right-hand side) shows the SSA decomposition of ΔLOD. In addition to decade variations, exceeding all other oscillations by more than one order of magnitude (92%), quasi-6-year variations are the next largest contributors (3%) to the spectrum of interannual variations in LOD. These variations are formed from a set of components in the band of 5- to 8-year periods. The causes of their excitation are questionable (interaction between the mantle and the inner core, atmospheric–ocean dynamics, and solar activity). Quasi-periodic 2- to 3-year variations in LOD are completely determined by variations in the corresponding χ_3 function (AAM) at the same frequency, thus reflecting quasi-2-year variations in zonal winds in the tropical stratosphere (Sidorenkov, 2002). Therefore, no variations with a period of 2–3 years are revealed in the variations in LOD of the eopAO series (from 1956), where the effect of the atmospheric–ocean dynamics is taken into account. The main components in the χ_3 functions (AAM and OAM) have a seasonal nature (a year and half of a year).

4.3. *Solar and Geomagnetic Activity*

Quasi-periodic 5- to 6-year components are present in the structure of SSN and SSAr series, as well as in the structure of shorter F10.7 and FI series, with a contribution to the total spectral power of about 1–2%, while 2- to 3-year components are only present in the FI series with a contribution of 1% (Fig. 2).

There is a common quasi-harmonic ~1.2-year component in the structure of geomagnetic indices (Ap and Dst) in the low-frequency band; it contributes about 2% to Dst and about 1% to Ap. There is also a 5- to 6-year component in the Dst series with a contribution of about 6%. We have already mentioned that no adequate excitation factors are revealed for the 5- to 7-year component in the ΔLOD series; therefore, the presence of similar components in the solar activity and, especially, Dst series allows one to suppose the geomagnetic excitation of this component in the ΔLOD series.

There is a set of components in the range 1.1–1.3 years in the data on total solar irradiance (TSI). Excluding the contribution of the main solar cycle, these components contribute 11.5% in total. Despite the insignificant contribution of this component to the total variability of the solar constant, the effect of this factor on CW modulations should not be excluded.

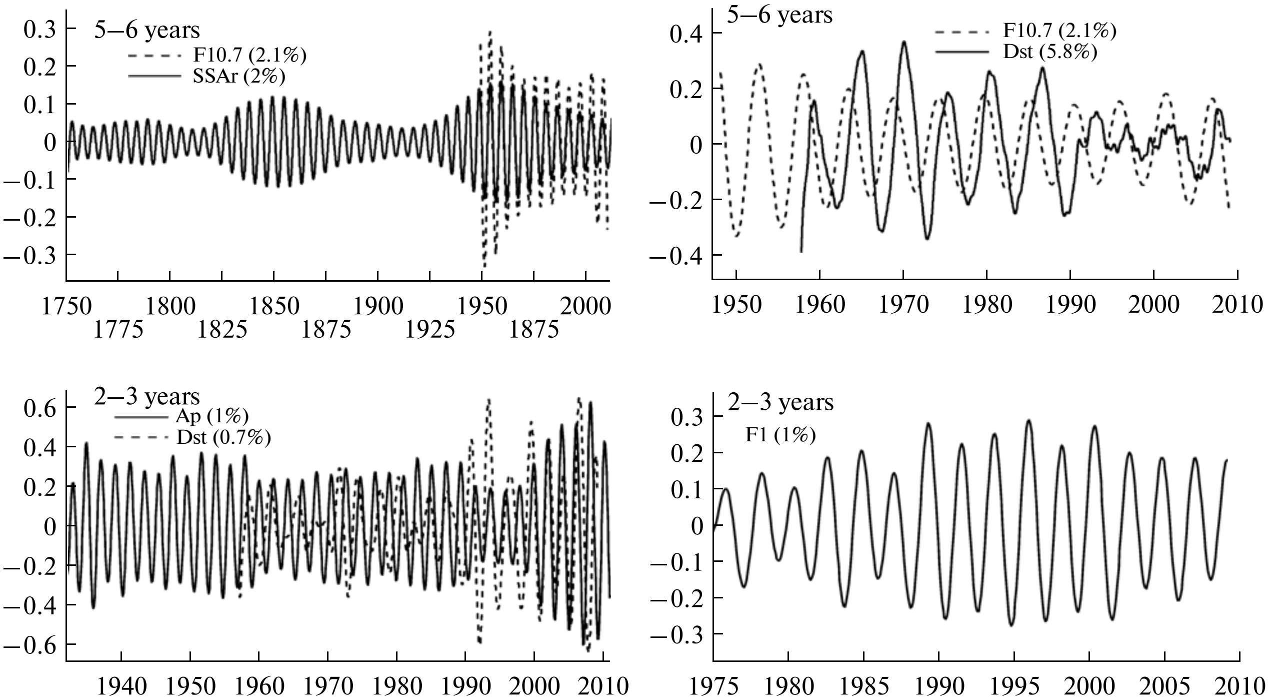

Fig. 2. (Top) 5- to 6- and (bottom) 2- to 3-year components in the SSA decomposition of solar (SSAr, F10.7, FI) and geomagnetic solar (Ap, Dst) activities.

The presence of similar components in the series of geomagnetic indices Ap and Dst intensifies the possible effect of the solar factor on CW modulation.

5. JOINT (MSSA) ANALYSIS OF DATA SERIES

5.1. Solar Activity, Geomagnetic Indices, and CW

The atmospheric–ocean dynamics is assumed to be one of the factors exciting free wobble of the poles (CW) (Munk and Macdonald, 1960). We have performed an MSSA series decomposition of the pole coordinates {Xp, Yp}, SSN, and the corresponding χ_1 and χ_2 functions (AAM, OAM). It turned out that the functions of angular momenta of the atmosphere and ocean (χ_1 and χ_2) oscillate concurrently at the annual frequency of pole wobbles, but no concurrent solar activity (SSN) is observed in this case. However, four components with significant amplitudes and corresponding to weak CW components of 1.16 (1.8%), 1.24 (0.9%), and 1.22 (2.8%) years have been distinguished from the MSSA decomposition of {Xp, Yp} and SSN. This can be an indication of the solar activity effect on the modulation of the CW amplitude without an atmosphere- and ocean-mediated influence. The results of a joint MSSA series decomposition of {Xp, Yp} and Dst, where three components with significant amplitudes were distinguished, corresponding to three weak CW components of 1.24 (1.9%), 1.1 (0.7%), and 1.16 (0.5%) years, can indicate the same (Fig. 3). The amplitudes of the components behave synchronously; i.e., a change in the amplitude of a component of the pole coordinates corresponds to an analogous change in the amplitude of the corresponding Dst component—a period of low magnetic activity corresponds to an increase in the CW amplitude. A comparison of {Xp, Yp} and Ap gives a similar result, i.e., 1.16 (1.7%), 1.22 (2.8%), and 1.1 (0.4%) years.

The joint MSSA decomposition of SSAr and the R_{CW} centroid radius (Fig. 4, left part), estimated after the removal of the mean pole wobble from the {Xp, Yp} series, gives the most interesting result in the region of secular variations.

About 40-year variations in the CW amplitude agree with solar activity (the significance level is 9%) with minimal phase discrepancies: the CW amplitude increases with solar activity. Forty-year variations in the CW amplitude were first noted in (Kostina and Sakharov, 1985). The cross-correlation function of these components shows just a 40-year maximum and about a 10-year phase shift.

5.2. Solar Activity, Geomagnetic Indices, and ΔLOD

A joint MSSA decomposition of SSAr and the functions of atmospheric–ocean angular momenta for the axial component (χ_3) shows a good spectral correspondence between these series in the region of our interest (Fig. 5). Components of the angular momenta with 5- to 6-year periodicity are almost synchronous (AAM to a low degree) with SSAr and spectrally equivalent at 1.6% level. The 2- to 3-year AAM component (1.2%) is almost opposite in phase with SSAr, while the corre-

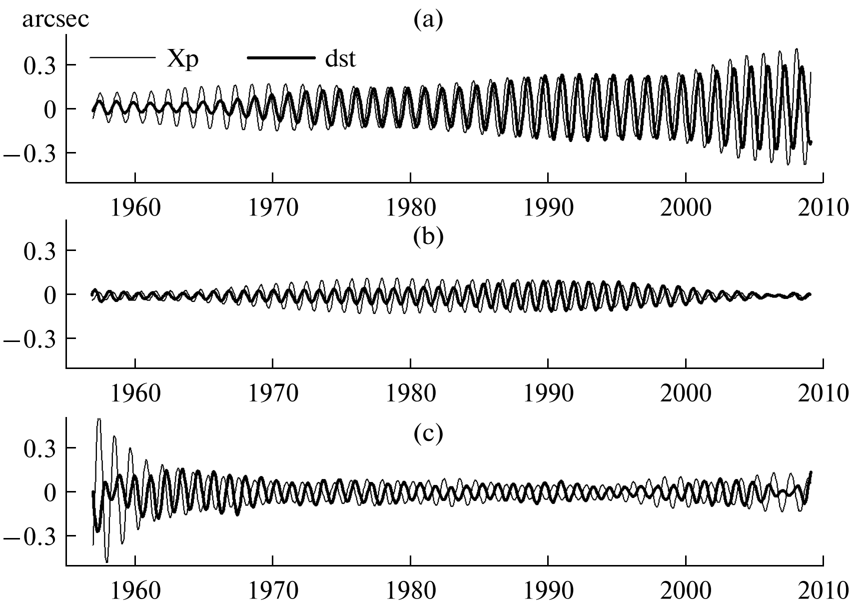

Fig. 3. MSSA decomposition of the pole coordinates {Xp, Yp} and Dst series (scaled). The periods of the components are equal to (a) 1.24, (b) 1.1, and (c) 1.16 years, respectively.

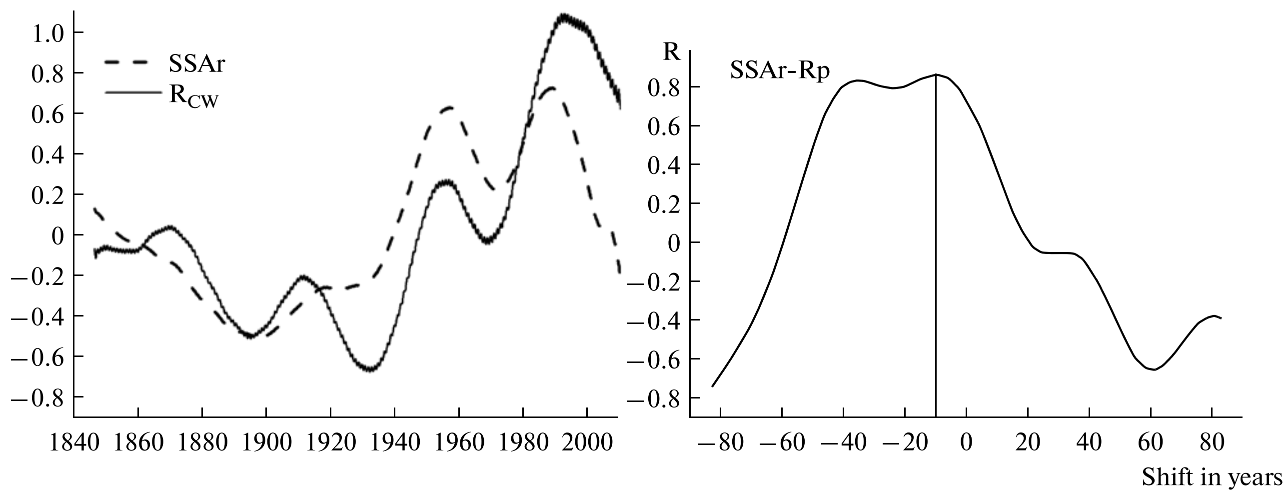

Fig. 4. MSSA decomposition of the SSAr series, the R_{CW} centroid radius (left part), and their cross-correlation function (right part).

sponding OAM component is weakly visible in the MSSA spectrum at this frequency. This component is weakly visible in long solar activity series too; therefore, only the SSAr–AAM dependence should be considered significant at this frequency band.

MSSA decomposition of ΔLOD and SSAr over the whole range from 1750, where the ΔLOD resolution is equal to one value per year, no correspondence between the series in a 5- to 6-year interval is revealed. However, the concurrency between the Earth's rotation rate and solar and, especially, geomagnetic activities in the interval from 1956 is evident (Fig. 6) for shorter and more detailed ΔLOD series (eopAO), in which the influence of the atmospheric–ocean dynamics is taken into account. Let us note the dependence of the decomposition results on the length of representation. This causes difficulties when comparing results with different lengths of representation.

There is no noticeable correspondence between ΔLOD and SSAr in the region of secular variations, although both of these series have the highest spectral power there. However, a comparison of low-frequency variations in these series gives a good synchronization if the solar activity series is shifted by 94 years towards the past.

In this case, a secular increase in solar activity with a delay of 94 years results in the acceleration of the Earth's rotation (Fig. 7). This result, obtained on the basis of 200-year history of observations of the Earth's

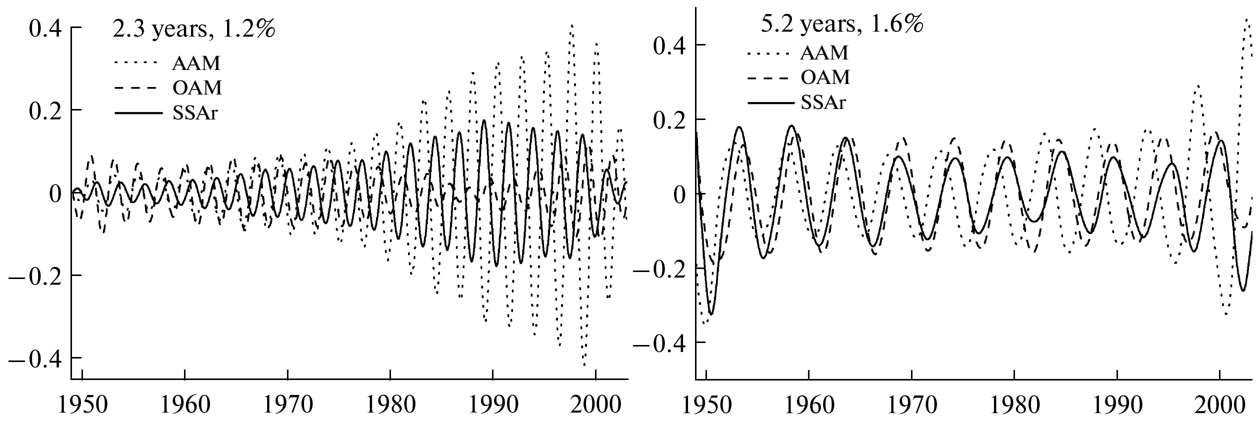

Fig. 5. MSSA decomposition of SSAr and A-OAM.

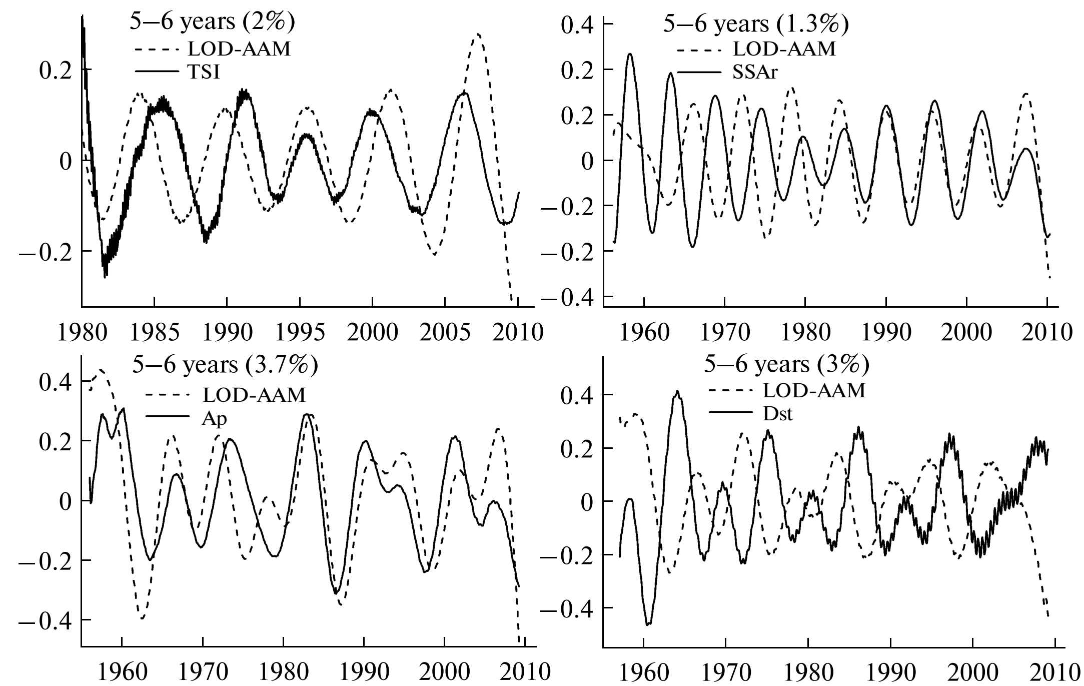

Fig. 6. Components (5- to 6-year) of MSSA of different series of solar and geomagnetic activities in comparison with the ΔLOD series.

rotation rate, was obtained earlier in (Duhau and Martinez, 1996) and, probably, is not random.

Since the short eopAO series is corrected for the influence of atmospheric–ocean dynamics χ_3 (AAM and OAM), where 2- to 3-year components totally manifest themselves, as has been mentioned above, then no corresponding components are revealed in the joint analysis of ΔLOD and solar activity.

6. EARTH'S GEOMAGNETIC ACTIVITY AND ΔLOD

The comparison of low-frequency Earth's rotation rate with long-term variations in the rate of the secular trend in the Earth's geomagnetic field (SV_N, SV_E, and SV_U) is the most interesting. Usually, jerks (points of change in this rate) are compared with the corresponding momenta of ΔLOD (Greiner-Mai, 1995; Holme and de Viron, 2005). Jerks are recorded from observation results at geomagnetic observatories, which is not always done globally and has a long (sometimes up to several years) delay at different observatories. This effect of delays and the spreading of jerks is assigned to regionally varying conductivity of the mantle (Alexandrescu, 1996). The rate of the east component (SV_E), averaged over the best European stations, is commonly used, as it represents variations in the Earth's geomagnetic field best of all.

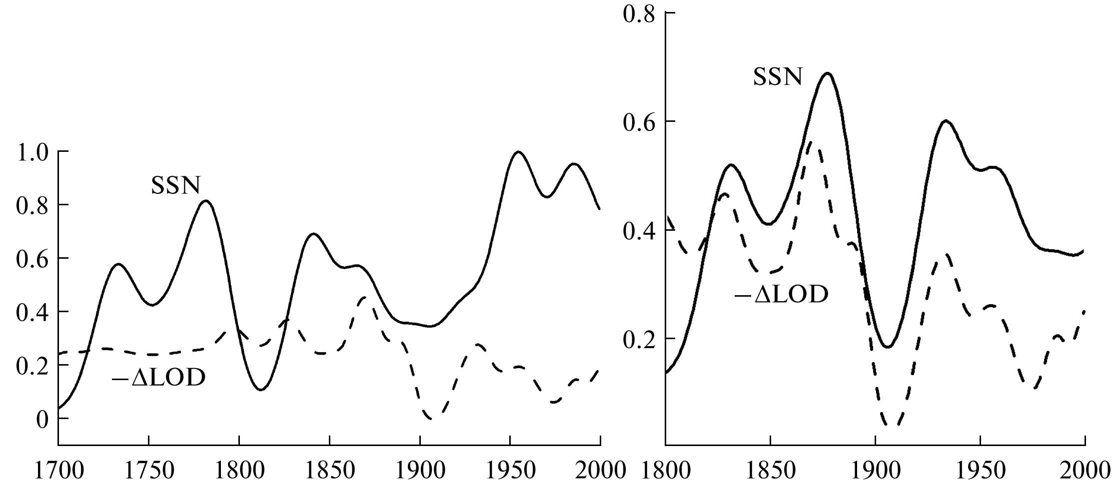

Fig. 7. Comparison of secular variations in SSN and ΔLOD; (right part) with a 94-year shift towards the past for SSN.

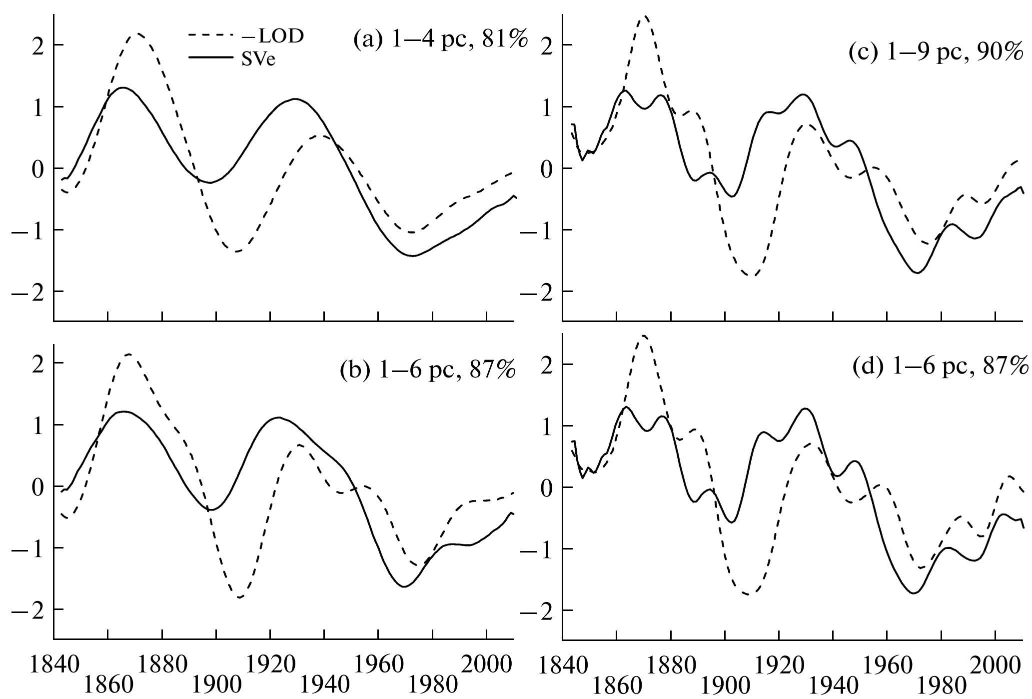

Fig. 8. Steps of MSSA restoration of components and their contributions when studying jointly SVe and −ΔLOD (the value corresponds in sign to the Earth's rotation rate); pc means principal components.

According to different assessments, the time of jerk shielding, i.e., the time of its "leakage" from the core–mantle boundary to the corresponding recording instruments on the Earth's surface, is from several to 20 years. Therefore, the authors of many works try to detect a corresponding feature in the behavior of the Earth's rotation in the past relative to recorded jerks. The only exceptions are the works (Holme and de Viron, 2005; Nakada, 2009), where direct, i.e., without any delay, manifestations of jerks have been revealed in certain cases.

A comparison of refined monthly INTERMAGNET geomagnetic data (Chulliat and Telali, 2007) for a part of the material (56 stations beginning from 1901) with annual average observatory data has not revealed differences between them in secular variations, but there were observed seasonal variations in the series. Therefore, we used annual average data from all available geomagnetic observatories (172 stations) with observational history longer than 25 years to form a combined SV_E series for the Northern Hemisphere. These data were also studied by the MSSA along with com-

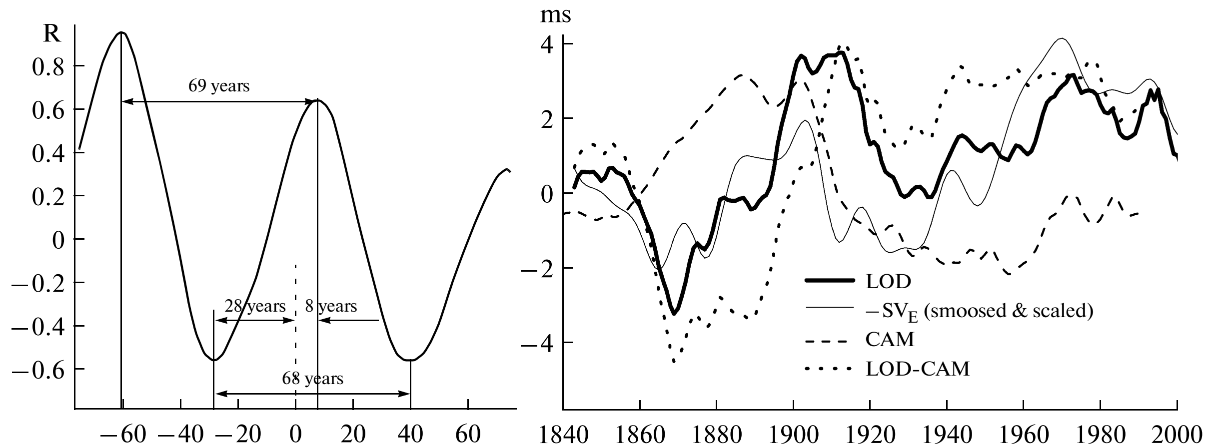

Fig. 9. Unbiased estimate of the cross-correlation between the ΔLOD and SV_E series (left part). A comparison of the SV_E, ΔLOD, and CAM series with the ΔLOD series, taking into account CAM (right part).

bined ΔLOD series, which also had a resolution of one value per year (Fig. 8).

When series are restored step-by-step with an increase in the number of the main components, in the SV_E series, additional curve-breaking points appear sequentially; they should be interpreted as ever-weaker (local) jerks. Further addition of components only increases the noise component. As is seen, all peculiarities of SV_E precede the corresponding features in the ΔLOD series, which is especially evident beginning from the 20th century, when the accuracy and number of stations increased. This important point can be defined more accurately by means of calculations of the cross-correlation function of these series (Fig. 9, left part).

As is seen, the delay is equal to 8 years; i.e., the Earth's rotation rate increases eight years after (for the period of observations on average) an increase in the rate of the eastern component of the Earth's geomagnetic field. The main and, which is most important, common period of their variability is equal to 68–69 years. The similarity between the details on the curves in Fig. 9 and the strictly periodic curve of these series do not allow for the possibility of another interpretation; i.e., the recorded features of secular variations in the rate of change in the geomagnetic field precede the corresponding variations in the Earth's rotation rate.

The core angular momenta are calculated by the model in (Pais and Hulot, 2000) by the International Earth Rotation Service; therefore, the contribution of these model data to the Earth's rotation rate can be estimated. All of the above-mentioned series are compared in Fig. 9 (right part). It is evident that the model does not exclude real variations in ΔLOD. This is probably related to a strongly underestimated conductivity of the mantle in the model, which, according to recent data (Ohta et al., 2012), can be increased significantly due to the discovery of FeO conductivity under the conditions of mantle temperatures and pressures. In any case, the time sequence of the geomagnetic field and Earth rotation rates follows from a comparison of their secular variations; i.e., the first features of the geomagnetic field are recorded and then they show in the Earth's rotation rate.

7. DISCUSSION AND CONCLUSIONS

We may assume that the electromagnetic effect of the solar wind during magnetic storms can be one of the excitation factors of variations in the CW amplitude and the Earth's rotation rate. The presence of magnetic interactions between processes that occur at the core–mantle boundary provides for the background angular momentum transfer from the core to the mantle. Variations in the magnetic field during magnetic storms induce currents in the mantle. The depth distribution of these currents is determined by the conductivity of rocks composing the Earth's interior. Based on the well-known estimates of changes in the conductivity with depth, we may assume the origination of variations in the Earth's magnetic field caused by magnetospheric processes at a depth of up to 1000–2000 km. In this case, rapid variations in the magnetic field are absent at these depths, and only slow variations are observed with periods corresponding to variations in the magnetic activity of the Sun. This can explain the agreement between the solar activity parameters and the variations in the ERP within 1- to 8-year intervals, studied in this work. A variation in the magnetic field due to solar activity can be considered as a controlling factor of the core–mantle magnetic interaction. In this case, the direct contribution of solar wind particles to variations in the Earth's rotation vector momentum is negligible.

Thus, the following conclusions can be drawn from the results of this work.

The correspondence between the geomagnetic activity (Dst, Ap) and weak CW components has been revealed by MSSA. The behavior of the amplitude of each component is synchronized with geomagnetic activity; i.e., a variation in the amplitude of each CW component corresponds to a similar variation in the amplitude of the corresponding component of geomagnetic activity. In the region of secular variations in the CW amplitude, about 40-year variations in it agree with solar activity: the CW amplitude increases with solar activity.

Analyzing the functions of geophysical excitation χ_3 (OAM and AAM) jointly with variations in solar and geomagnetic activity, ~2.3- and ~5.2-year components have been revealed. The best spectral correspondence between these processes is observed for the 5.2-year component: the atmospheric–ocean dynamics at this frequency increases with solar activity. For the 2- to 3-year component, the dynamics of solar activity is opposite in phase only with atmospheric function χ_3.

The Earth's rotation rate is closely related to solar and, especially, geomagnetic activity in the region of 5- to 6-year periods. Beginning from the second half of the 20th century, an increase in solar activity generally corresponds to a decrease in the Earth's rotation rate (vice versa for Dst) in this region of periods, although phase variations sometimes strongly disturb the correlation between these processes.

In the region of the strongest secular variations, no regular correspondence is observed between solar activity and the Earth's rotation rate; however, the results of the work (Duhau and Martinez, 1996) can be confirmed: variations in the Earth's rotation rate repeat secular variations in solar activity with a delay of 94 years. This law has been true for the last 200 years, i.e., almost the entire modern observation history.

The time sequence of the Earth's geomagnetic field and rotation rates follows from a comparison of their secular variations; i.e., first, the features of the geomagnetic field are recorded and then they are reflected in the Earth's rotation rate with an average observation delay of eight years.

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