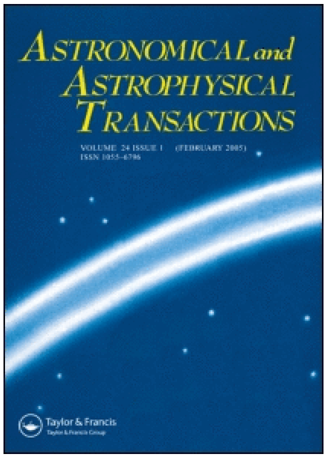

Astronomical & Astrophysical Transactions

The Journal of the Eurasian Astronomical Society

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Physics of the Earth's rotation instabilities

N. S. Sidorenkov [a]
[a] Hydrometeorological Centre of Russia, Moscow, Russia

Online Publication Date: 01 October 2005
To cite this Article: Sidorenkov, N. S. (2005) 'Physics of the Earth's rotation instabilities', Astronomical & Astrophysical Transactions, 24:5, 425 - 439
To link to this article: DOI: 10.1080/10556790600593506
URL: http://dx.doi.org/10.1080/10556790600593506

Astronomical and Astrophysical Transactions
Vol. 24, No. 5, October 2005, 425–439

Physics of the Earth's rotation instabilities

N. S. SIDORENKOV*

Hydrometeorological Centre of Russia, 11–13 Bolshoi Predtechensky Pereulok, Moscow 123458, Russia

(Received 7 November 2005)

This paper generalizes the results of investigations on the instabilities of the Earth's rotation and related geophysical processes. Long series of observations of the Earth's orientation parameters are demonstrated. The tidal variations in the length of the day are described. The temporal variations in the atmospheric angular momentum and their contribution to the instabilities of the Earth's rotation are studied. The mechanisms of seasonal variations in the length of the day and polar motion are discussed. The probable geophysical processes responsible for the decades-long (2–100 years) instability of the Earth's rotation are discussed.

Keywords: Earth; Rotation; Instabilities

1. Astronomical data

The Earth's diurnal rotation has always been used for measuring the time. In astronomy and geodesy, this rotation serves as a basis for various systems of coordinates. However, as the Earth rotates, its speed varies, the geographic poles move, and the axis of rotation nutates in space. This instability distorts the coordinates of celestial and terrestrial objects. The processes that occur on the planet and the specific features of the structure and physical properties of the Earth's interior cause rotational irregularities and polar motions.

The constancy of the Earth's rotation began to be doubted following E. Halley's discovery of the secular acceleration of the Moon's motion in 1695. I. Kant was the first to suggest the idea of secular deceleration of the Earth's rotation under the action of tidal friction in 1755. At the close of the nineteenth century, evidence was obtained of irregular fluctuations in the planet's speed of rotation and the motion of the geographic poles. Since then regular observations of these phenomena have been carried out.

The speed of rotation of the Earth can be characterized by the dimensionless value

$$\nu = \frac{\delta\omega}{\Omega} = \frac{\omega - \Omega}{\Omega} = -\frac{\Pi_{\mathrm{E}} - T}{T} \equiv -\frac{\delta\Pi}{T}, \tag{1}$$

*Email: sidorenkov@mecom.ru

Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790600593506

where Π_{E} is the length of the Earth's day, T is the length of the reference (atomic or ephemerid) day, which is equal to 86 400 s, $\omega = 2\pi/\Pi_{\mathrm{E}}$ is the angular velocity of the Earth's day and $\Omega = 2\pi/86\,400\ \mathrm{rad\,s^{-1}}$ is the angular velocity of the reference day.

The shorter the Earth's day, the faster is the rotation of the Earth. Before a very precise atomic clock was created, the speed of rotation had been controlled by comparing the coordinates of planets observed and calculated (using celestial and mechanical theories). This is how it became possible to gain an insight into the variability of rotation of the Earth within the last three centuries (figure 1). From the beginning of the seventeenth to the middle of the nineteenth centuries, the speed of rotation of the Earth varied little. From the second half of the nineteenth century onwards, considerable irregular fluctuations of the angular speed of the Earth's rotation with a typical time of the order of 60–70 years have been observed. The highest speed of rotation of the Earth was recorded in 1870, when the Earth's day was shorter by 0.003 s than that of the reference day; the lowest speed was in 1903, when the Earth's day was 0.004 s longer than that of the reference day. From 1903 to 1934, the Earth's rotation was accelerating; from the end of the 1930s to 1972, its deceleration was observed; from 1973 onwards, the Earth's rotation has been accelerating. The variation in the angular speed of the Earth's rotation that was observed in the twentieth century (from 1903 to 1972) is often called the 60–70-year-long variation. In the nineteenth century, a variation of about the same period was recorded from 1845 to 1903. No 60–70-year-long variations were traced in the seventeenth and eighteenth centuries. Unfortunately, the data for these centuries have a low resolution because, at that time, the intervals between observations were sometimes as long as 29 years.

The measurement accuracy of the irregularity of the Earth's rotation improved in 1955, when astronomers began to use the atomic clock. This provided an opportunity to record the fluctuation of the speed of the Earth's rotation with a period of more than a month. Average monthly values of the rotational speed of rotation in 1955–2000 are shown in figure 2. The lowest speed of rotation was recorded in April and November and the highest in January and July. January's maximum is significantly lower than July's. The difference between the minimum value of the length of day in July and the maximum value in April or November is 0.001 s.

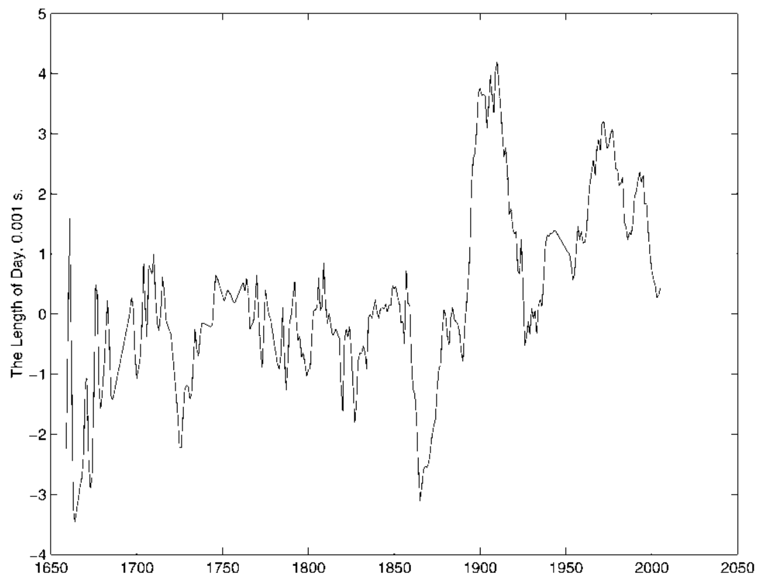

Figure 1. Changes in the length of the day over the last 350 years.

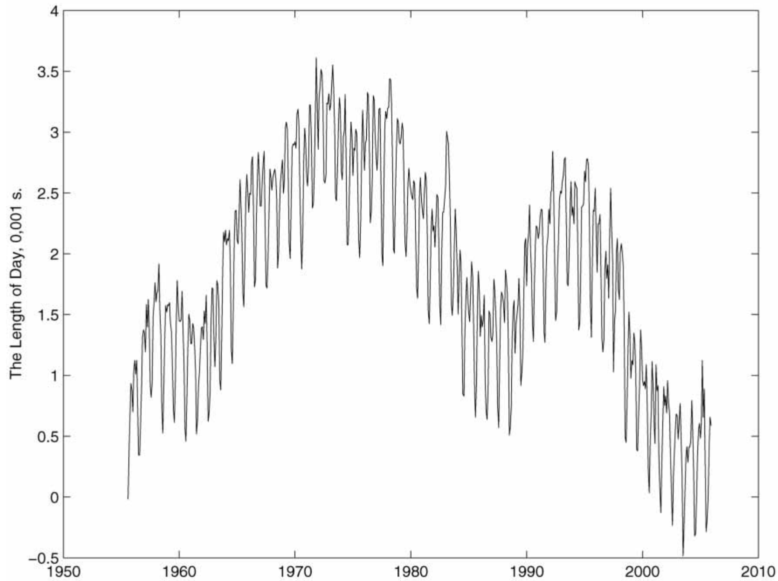

Figure 2. The monthly mean values of the length of the day in 1955–2005.

Seasonal variations are usually described by the sum of the annual and semiannual harmonics. Their amplitudes and phases vary from year to year, manifesting interesting regularities. The amplitude of the annual harmonics varies with a typical time of 6 years, and that of the semiannual harmonics with a typical time of about 2 years. The average magnitudes of the amplitudes of the annual and semiannual harmonics are 0.000 35 and 0.000 32 s, respectively.

In the 1980s, astro-optical observations were replaced by new measurement methods: very-long-baseline interferometry, satellite laser location, lunar laser location, global positioning system and so on. The accuracy of measurements of the universal time increased by an order of two. As a result it became possibile to study fluctuations in the speed of rotation of the Earth with daily periods, and in some special series of observations with a period of several hours. Figure 3 shows the day-to-day course of the length of the day in 2004–2005. Here, in addition to the weather-related seasonal variation, one can clearly see the tidal oscillations in the length of the day. Their range is a little smaller than the range of seasonal variations, but their periods are several magnitudes shorter than the seasonal periods (they are close to 14 days).

An efficient tool for investigating the cyclic recurrences is spectral analysis. It consists, firstly, of representing the variations studied as the sum of elementary harmonics and, secondly, of identifying the dependence of the mean square amplitudes of these harmonics on their frequency or period, *i.e.*, in finding a spectral function. In tidal variations in the Earth's rotational speed, there are components with periods equal to a year, half a year, and 13.7, 27.3 and 9.1 days. Spectral analysis of the 350-year series of the average annual values gives the maximum spectral density for a period of about 70 years. The variations with this period have been especially pronounced in the last 150 years. In the early twentieth century, the amplitude of the 70-year-long variations was as large as 0.002 s.

It is not only the Earth's angular velocity that varies. Our planet has small nutations relative to the axis of rotation. Therefore, the points at which the axis intersects the surface of the Earth (instant poles of the Earth) are in motion. They travel on the Earth's surface around the middle pole in the direction of the Earth's rotation, *i.e.*, from west to east. The trajectory of

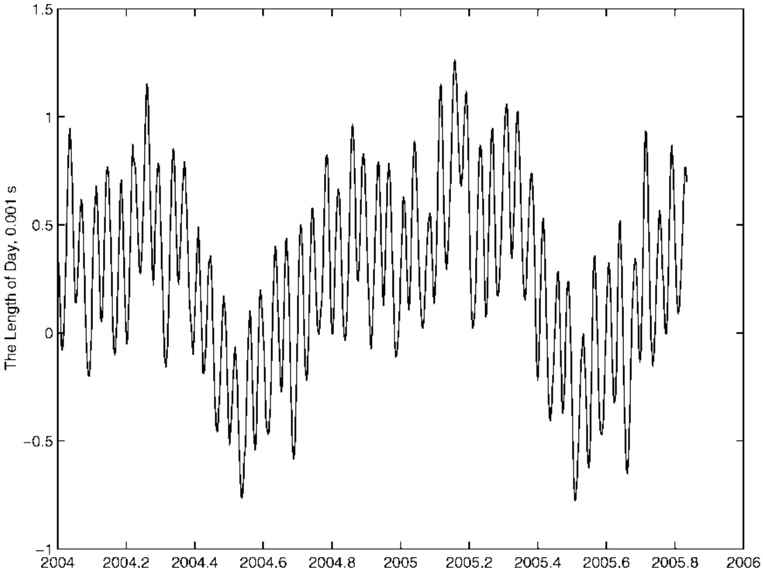

Figure 3. The daily values of the length of the day during 2004–2005.

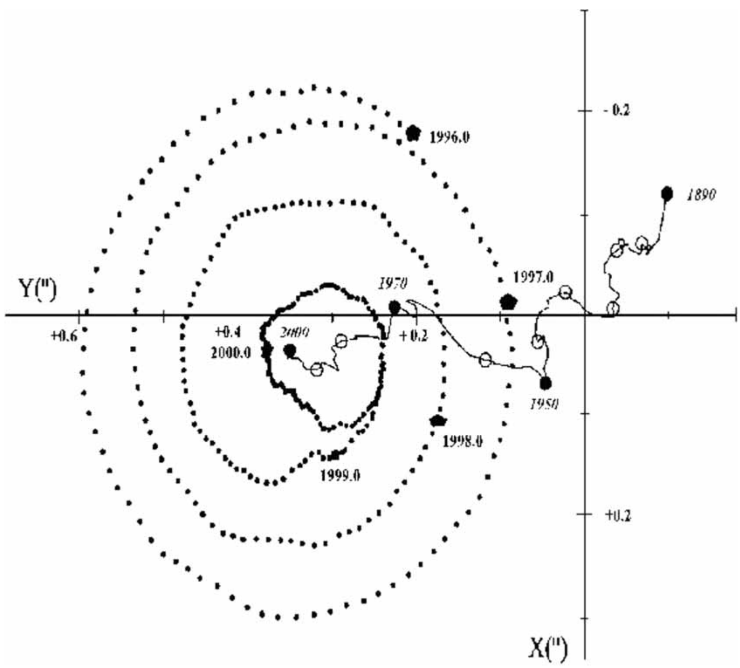

Figure 4. The polar motion trajectory in 1996–2000. The continuous polygonal curve denotes the path of the mean pole in 1890–2000.

the polar motion is like a helix, which periodically twists or untwists. By way of example, the path of the instant North Pole for 1996–2000 is given in figure 4. Its maximum deviation from the mean position was registered in May–July 1996. Then the pole started to twist, and this continued up to 2000, when it most closely approached the centre of the helix. In 2001–2003, the pole untwisted and moved off its mean position.

The largest deviation of the instant pole from the mean position does not exceed 15 m. The polar trajectory's twisting and untwisting are explained by the fact that it performs two periodic motions: the free motion or the Chandler motion (named after Seth Chandler who discovered it in 1891) with a period of about 14 months, and the forced motion with a period of 1 year. The Chandler motion of the poles occurs when the Earth's rotation axis deviates from the axis of the Earth's maximum moment of inertia. The polar motion caused by the effect of periodic forces of the atmosphere or hydrosphere on the Earth is called forced. The period of free movement depends on the planet's dynamic compression and elastic properties rather than on the exciting force period typical of forced motion. The summation of these motions produces the pattern observed.

Analysis of the polar coordinates over the last 110 years shows that the forced motion occurs along an ellipse from west to east. The values of major semiaxes of the ellipse vary in the range from 3.4 to 2.7 m, those of minor semiaxes from 2.5 to 1.8 m, those of eccentricities from 0.15 to 0.46, and those of the eastern longitude of the major semiaxis from latitude 205 to 145 °E.

The Chandler polar motion has an almost round trajectory. It is characterized by even greater variability of parameters. The radius of the free motion has an amplitude modulation with a period of about 40 years. The maximum radius (9 m) was observed in 1915 and 1955, and the minimum radius (2 m) in 1930.

At present the helical centre is some distance away from the international conventional point of origin. The reason for that is the secular polar motion. To eliminate the annual and the Chandler components from the polar coordinates, we obtain the coordinates of the mean pole. The mean pole is in motion too. Its path for 1890–2000 is shown in figure 4. In the observation period, the mean pole was shifting along a complicated zigzag curve with a predominant direction towards North America (meridian latitude, 290 °E) at a speed of about 10 cm year^{-1}.

2. Nature of the periodic variations

The Earth's figure is close to an ellipsoid of revolution. When the Moon and the Sun do not lie in the plane of the terrestrial equator, their attractive forces tend to turn the planet in such a way that the equatorial bulge of its figure is located along the line that connects the centres of the masses of the Earth, the Moon and the Sun. However, the Earth does not turn this way; instead, it precesses under the action of the gravitational torque. The axis of the Earth's rotation slowly describes a cone around a perpendicular to the plane of the ecliptic (figure 5). The cone point coincides with the centre of the planet. The equinoctial and solstice points move along the ecliptic towards the Sun making a rotation every 25 600 years (the speed of movement is 1 ° per 72 years).

The moments of attractive forces that act on the equatorial bulge vary depending on the position of the Moon and the Sun relative to the Earth. When these planets are in the plane of the terrestrial equator, the moments of forces disappear and, when the declinations of the Moon and the Sun are maximal, the magnitude of the moment is the highest. Such fluctuations in the moments of attractive forces are responsible for nutations (from Latin *nutatio* meaning wiggle) of the Earth's rotation axis, which are composed of a series of small periodic terms. The major periodic term has a period of 18.6 years, *i.e.*, the time of the revolution of nodes of the lunar orbit. The motion with this period is elliptical. The major axis of the ellipse is normal to the direction of the precession motion and is equal to 18.4", while the minor axis is parallel to it and is equal to 13.7". Consequently, the axis of rotation of the Earth describes in the coelosphere a wave-like trajectory with points spaced at an average angular distance of about 23 ° 27 from the ecliptic pole (figure 5).

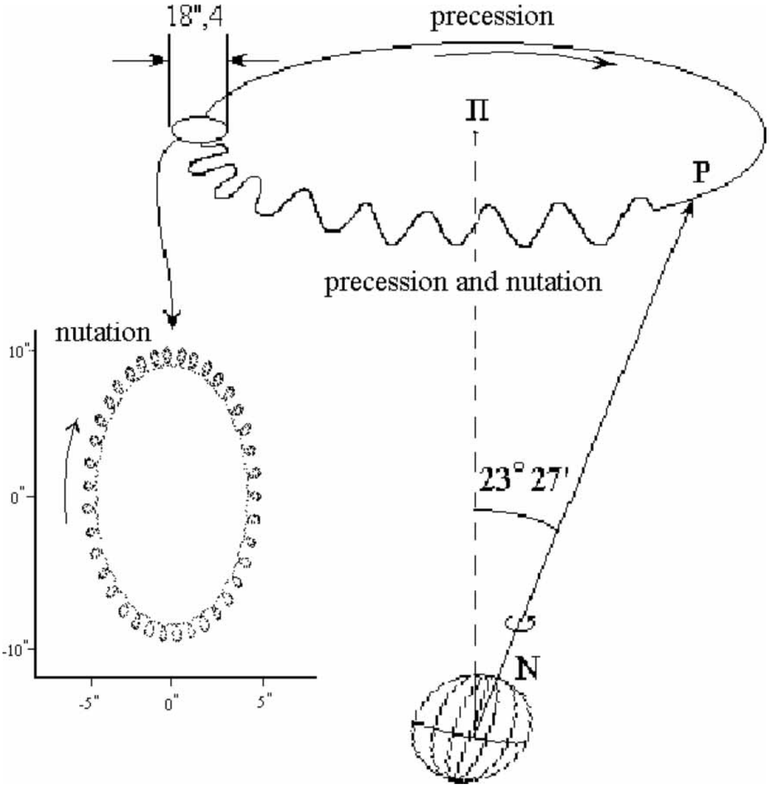

Figure 5. Diagram of the spatial motion of the Earth's rotation axis for an extraterrestrial observer.

Tidal bulges move along the Earth's surface following the Moon and the Sun from east to west, *i.e.*, in the direction reverse to the diurnal rotation of the Earth. Naturally, this causes the emergence of frictional forces in the oceans and in the Earth, which decelerate the planet's rotation and are responsible for the secular slowing down of the Earth's rotation. Estimates show that the length of the day should become 0.003 s longer over 100 years. Consequently, the irregularities of the Earth rotation presented in figures 1 and 2 are almost independent of the tidal friction and are caused by other reasons.

Terrestrial tides play a noticeable role in the fluctuations in the rotational speed with periods less than a month. The tide-generating force stretches the planet along a straight line connecting its centre with that of the exciting body–the Moon or the Sun. In addition, the Earth's compression increases when the axis of elongation coincides with the equator plane and decreases when the axis deviates towards the tropics. The moment of inertia of the compressed Earth is larger than that of the undistorted ball-shaped planet. As soon as the Earth's angular momentum (the product of its moment of inertia by the angular velocity) must be constant, the speed of rotation of the compressed planet is lower than that of the undistorted planet. As the Moon and the Earth–Moon system move, the declinations of the Moon and the Earth vary, as well as the distances from the Earth to the Moon and the Sun. That is why the tide-generating force is time variable. Accordingly, the compression of the Earth changes too, which, in the end, causes the tidal irregularity of its rotation. The most essential of these changes are fluctuations with half-monthly and monthly periods.

What is the reason behind the tideless irregularity of the Earth's rotation and polar motion? Many processes can affect the rotation of the Earth. These include changes in the distribution of air masses in the atmosphere, blankets of snow, ice covers, precipitation and vegetation on the Earth's surface, changes in the level of the world's oceans, interactions of the Earth's core and mantle, volcano eruptions, earthquakes, actions of external forces, and so on. Careful assessments of the contributions of the above-listed processes allowed us to identify the most important of these.

Within a year, air and moisture masses redistribute among continents and oceans, and between the northern and southern hemispheres. Thus, in January, the air mass over Eurasia is greater than that in July by 6×10^{15} kg. From January to July, 4×10^{15} kg of air masses is transferred from the northern hemisphere to the southern hemisphere [1]. During winter, snow is accumulated in the northern areas of Eurasia and North America. In spring, water returns to the world's oceans. All this alters the Earth's moment of inertia and affects its rotation. Estimates show that the seasonal redistribution of air and moisture masses has little effect on the seasonal irregularity of the planet's rotation but almost fully determines the forced polar motion.

The Chandler polar motion must decay with time, because the energy of the free polar motion converts into heat on the Earth. The absence of decay of the free polar motion indicates that there are processes that continuously maintain it. The excitation of the polar motion have usually been estimated near the principal resonance, namely the Chandler frequency. However, in the Earth–ocean–atmosphere system, nonlinear oscillations and excitation of the Chandler polar motion occur primarily at the combinative frequencies of the Chandler frequency (with periods of 2.4, 3.6, 4.8 and 6 years), rather than at the principal resonant frequency [1, 2]. The temporal variations in the intensity of the global geophysical processes (El Nino, Southern Oscillation, etc.) lead to instabilities in the Chandler polar motion excitation process and, thus, to variations in its characteristics (the amplitude, phase, damping decrement, etc.).

Many investigations have demonstrated that the main reason for the seasonal irregularity in the Earth's rotation is atmospheric circulation. On average, the atmosphere moves from east to west relative to the Earth's surface at low latitudes and from west to east at moderate and high latitudes. The angular momentum of the predominant east winds is negative, and that of the west winds is positive. One might expect that these momenta compensate each other and that the angular momenta of atmospheric winds of both directions are always equal to zero. However, calculations show that the angular momentum of east winds is several times lower than that of west winds. The average annual angular momentum of atmospheric winds is $+14 \times 10^{25}$ kg m^{-2} s^{-1}. Its magnitude varies within the year from $+16.1 \times 10^{25}$ kg m^{-2} s^{-1} in April and November up to $+10.9 \times 10^{25}$ kg m^{-2} s^{-1} in August [1].

The angular momentum is a physical magnitude that cannot emerge or be destroyed. It can only be redistributed. In the case under consideration, the redistribution occurs between the atmosphere and the Earth. As the angular momentum of the atmosphere increases (the west winds become stronger, or the east winds become weaker), the angular momentum of the Earth decreases; *i.e.*, its rotation decelerates. On the contrary, when the angular momentum of the atmosphere decreases (the west winds become weaker, or the east winds become stronger), the Earth's rotation accelerates. The good agreement between the changes in the angular momentum of the atmosphere and that of the Earth in 1958–2001 is shown in figure 6. The magnitudes of deviation of the Earth's angular momentum are taken with the reverse sign. It can be seen that the courses of both curves coincide within the observational errors. Thus, the total angular momenta of the planet and the atmosphere remain invariable.

The fact that the angular momentum of winds is always positive indicates that the atmosphere rotates on its axis more rapidly than the Earth does. Assuming that the movement of the entire atmosphere is the rotation of a solid body, one can infer that the period of the atmosphere rotation on the axis is 23 h 36 min in April and November and 23 h 45 min in August. The average annual day of the atmosphere lasts 23 h 38 min, while that of the Earth lasts 23 h 56 min.

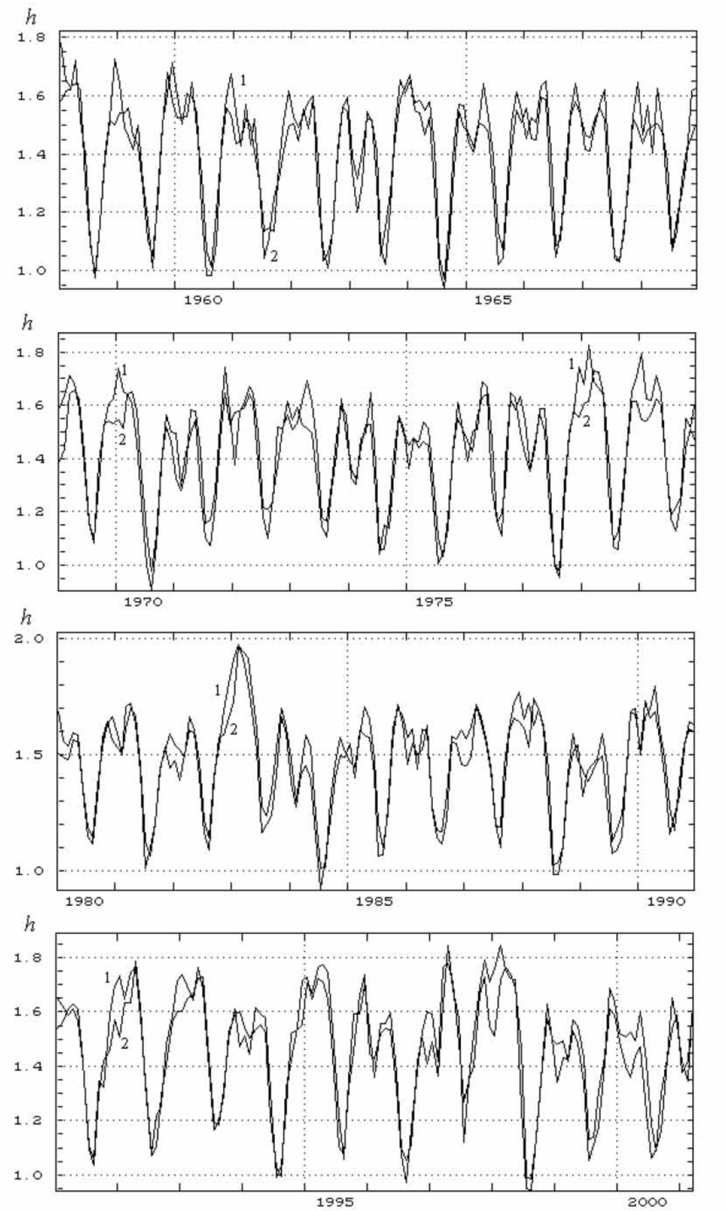

Figure 6. Synchronous changes in the relative angular momentum of the atmosphere (curves 1) and the Earth's angular momentum calculated with the opposite sign (curves 2) in 10^{26} kg m^{-2} s^{-1}.

There is an opinion that, as soon as the atmosphere leaves the Earth behind in the diurnal rotation, it must speed up the Earth's rotation. However, only changes in the angular momentum of winds affect the irregularity of the Earth's rotation. The atmosphere adopted the constant magnitude of the angular momentum of winds from the Earth at the time when atmospheric circulation was being formed. Then the speed of the Earth's rotation decelerated a little (the day became 0.0024 s longer) and has since remained the same. If the source that sustains winds in the atmosphere is exhausted, the atmospheric circulation will stop, and the duration of the day will return to its original value.

The atmosphere, which is non-uniformly heated by the Sun's rays, can be regarded as a heat engine. It converts thermal solar energy into kinetic wind energy. In this case, the warmest parts of the atmosphere function as a heater and the cold parts as a cooler. The air itself serves as an working substance.

The relative angular momentum for the entire atmosphere is determined by the sum of the inputs of the thermal engines existing in the atmosphere. These thermal engines are as follows:

(i) the first-kind thermal engines (FKTEs), which are caused by the contrasts between the temperatures of the poles and the equator;
(ii) the inter-hemisphere thermal engine (IHTE), which is caused by different amounts of heating of the atmosphere in the northern and southern hemispheres [1].

There are two FKTEs in the atmosphere. One of them takes place in the northern hemisphere and the other in the southern hemisphere. Each of these redistributes the atmospheric angular momentum between low and high latitudes and takes it from the Earth. It is clear that, the larger the contrast between the temperatures of the equator and the poles, the higher is the angular momentum taken from the Earth by the atmosphere. In each hemisphere the contrast between the temperatures of the equator and the poles varies with the yearly period. In winter, this contrast attains its maximum value, and in summer the minimal value. So, the atmospheric angular momentum of the northern hemisphere oscillates with the yearly period, the maximum value being in January and the minimum in July. In the southern hemisphere, the annual course of the angular momentum has the opposite phase; the maximum of the angular momentum occurs in July and the minimum in January. As a result, the annual variations in the angular momenta in the northern and southern hemispheres compensate each other, and their sum for the entire atmosphere is nearly constant. Thus, FKTEs do not affect the observational seasonal variations in the atmospheric angular momentum. On the other hand, the IHTE does not take angular momentum from the Earth but only redistributes it between the winter and summer hemispheres (the angular momentum is positive in the winter hemisphere, and negative in the summer hemisphere). Thus, at first sight, it seems that the IHTE does not influence the angular momentum variations for the entire atmosphere. However, this concept is not correct. In fact, the part of the atmosphere that participates in the IHTE work is excluded from the FKTE work. So, the IHTE suppresses the FKTE, decreasing ultimately the atmospheric angular momentum, which is taken the atmosphere from the Earth owing to the FKTE work. The larger the contrast in temperature, the greater this effect is. In January and in July, when the IHTE work is the most intensive, the angular momentum and, consequently, the length of day are reduced to their minimum values. In April and November, a temperature contrast between the northern and southern hemispheres is nearly absent, and the IHTE no longer works. So, the entire atmosphere takes part in the FKTE work, increasing the angular momentum and, consequently, the length of day up to their maximum values.

The thermodynamic analysis of these thermal engines shows that the seasonal variation h and, consequently, δP are not the sum of the annual and the semiannual harmonics but can be approximated in the form [1]

$$h \approx \delta P = C - |\Pi + E \cos(e - \varphi)|, \tag{2}$$

where δP is the length of the day, C is a constant, Π is proportional to the difference between the annual mean temperatures of the northern and southern hemispheres, E is proportional to the sum of amplitudes of the annual temperature variations in the northern and southern hemispheres, e is the longitude of the mean Sun and φ is the initial phase. Time variations in the values of Π, E and φ are much slower than those in the longitude e.

The difference between the minimum values of δP in July and January is caused by the fact that the atmosphere in the northern hemisphere is warmer on the average for the year than in the southern hemisphere ($\Pi > 0$). If $\Pi = 0$ (*i.e.*, overheating is absent), then the values of δP in July and January would be the same.

For April and November, the expression $\Pi + E\cos(e - \varphi)$ changes sign, and the derivative $\mathrm{d}(\delta P)/\mathrm{d}e$ of the length of the day undergoes abrupt changes. These peculiarities of seasonal variations in the length of day should be taken into consideration when smoothing is applied to observational data.

3. Nature of the decades-long variations in the Earth's rotation

These variations are too great to be explained in the same way as the seasonal variations, *i.e.*, by the redistribution of the angular momentum between the atmosphere and the Earth. In the period from 1870 to 1903, the deceleration of the rotational speed was such that the angular moment of the Earth decreased by 48×10^{25} kg m^{-2} s^{-1}. If this deceleration had been caused by the redistribution of the angular momentum between the Earth and the atmosphere, the wind's angular momentum in 1870 would have been 48×10^{25} kg m^{-2} s^{-1} greater than that in 1903. In other words, the wind's velocity in the atmosphere would have to have increased by more than three times (over 33 years, the velocities of the west wind would have been stronger and those of the east wind weaker by about 20 m s^{-1}). However, such drastic changes in wind velocities are not observed.

It is believed that the long-period irregularity in the Earth's rotation cannot be caused by the geophysical processes that occur on the Earth's surface. The decades-long (2–100 years) variations are usually ascribed to such intraterrestrial processes as the interactions of the planet's core and mantle [3, 4]. This hypothesis is supported by the close correlation between changes in the Earth's rotational speed and the fluctuations in the drift speed of its eccentric magnetic dipole with a typical time of the order of 60 years [5].

In recent years, we have found some empirical facts that allow us to treat this problem in a new fashion. The effect of the atmosphere on the Earth's rotation can be assessed not only by calculating the variations in the inertia moment and the angular momentum of the atmosphere, but also by computing the moments of forces that act on the Earth from the atmosphere. These are the moments of forces of the wind's friction on the underlying surface and the moments of forces of air pressure on the mountain ridges that stand in the way of winds. To determine these moments of forces, one needs the data on wind fields or atmospheric pressure in the surface layer over the whole planet. Knowing the total moment of forces, it is easy to calculate the acceleration and irregularity of the Earth's rotation. Using the monthly mean sea level pressure data for the 1956–1977 period, the variations in the length of the day were calculated by the torque approach [1, 6]. These calculations show that not only the seasonal fluctuations but also the decades-long fluctuations in the length of the day are caused by the friction of the atmosphere against the Earth's surface and by the atmospheric pressure on the mountain ridges. This result points to the existence of transfer 'by parts' of either the positive or the negative angular momentum via the surface layer of the atmosphere, which leads to the perennial irregularities in the Earth's rotation. However, no corresponding changes in the wind's angular momentum necessary to gain the balance have been observed. Hence, there should be some source of angular momentum generated into the atmosphere. It would be natural to suppose that the atmosphere gains angular momentum from the near-Earth space or from the Earth (in the process of the multiyear redistribution of water between the oceans and the land). Estimates have shown that the flow of the angular momentum of space due to the solar wind and the action of the interplanetary magnetic field is negligible, and further attention has focused on studying the role of water redistribution.

3.1 *Variations in the ice sheet masses*

As is well known, about 2% of all the water on the Earth is in a frozen state. The total mass of ice in the modern epoch is approximately equal to 28.4×10^{25} kg. Of this, 90% falls on the Antarctic ice sheet, 9% on the Greenland glacier and less than 1% on the remaining mountain glaciers. The area of ice sheets in Antarctica is 13.9×10^{12} m^2, the area of ice sheets in Greenland is 1.8×10^{12} m^2, and the area of mountain glaciers is 0.5×10^{12} m^2.

The mass of glaciers varies in time. For example, 12 000 years ago, a huge ice sheet, which had covered almost the entire Russian Plain and vast areas of Western Europe and North America, melted. During the minor climatic optimum (about 1000 years ago), the Greenland ice sheet had a considerably smaller mass than today. Such redistribution of water between the world's oceans and the ice sheets was accompanied by changes in the moment of inertia of the Earth and must have led to its irregular rotation and secular polar motion. On this basis, combined algebraic equations can be set up to relate the value of the Earth's rotational speed and the polar coordinates to the masses of ice in Antarctica and Greenland and water in the world's oceans [1].

These equations allow one to calculate the rotational characteristics of the Earth: the polar coordinates and the rotational speed of the Earth. If the masses of ice are unknown but data on the instability of the Earth's rotation are available, it is possible to solve the inverse problem: to compute the annual values of ice masses in Antarctica and Greenland and of water in the world's oceans from the polar coordinates and the rotational speed.

Unfortunately, we were unable to compare our series of computed masses of ice in Greenland and water in the world's oceans with observational data because of the lack of the latter. It was only for Antarctica that we were able to compare the calculated curve of changes in the ice mass with the observed curve (figure 7). The qualitative fit of the curves testifies to a possible relation between the perennial irregularity in the Earth's rotation and the fluctuations in global water exchange. Yet the calculated fluctuations in global water exchange are almost 29 times greater than the observed values.

These contradictory results indicate that the decades-long fluctuation in rotation observed are not irregularity due to the rotation and polar motion of the whole Earth but rather to changes in the speed of drift of the lithosphere in the asthenosphere. Indeed, the moments

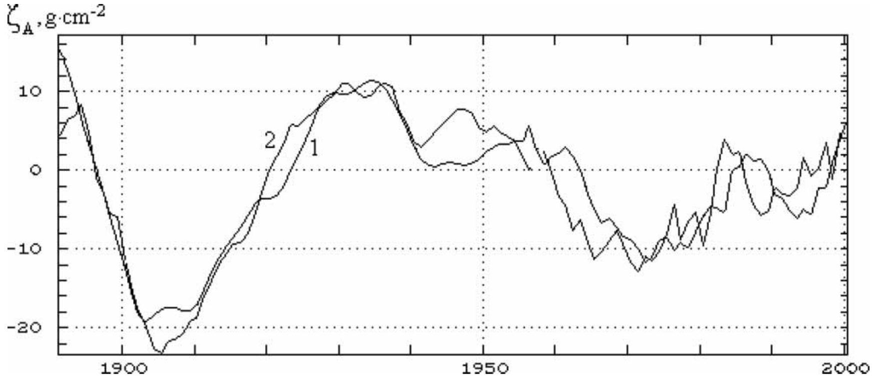

Figure 7. Temporal variations in the specific mass ζ_A (g cm^{-2}) of ice in Antarctica: curve 1, the theoretical value of ζ_A; curve 2, the empirical value of ζ_A [7].

of the like-sign forces arising in the process of fluctuation in global water exchange act for decades. It is possible that, with such long-term impacts, the matter of the asthenosphere underlying the lithosphere does not behave like a solid body but rather flows like a viscous fluid. Then the decades-long global water exchange can result in gliding of the lithosphere on the asthenosphere without having a noticeable effect on the Earth's deeper layers. During astronomical observations, changes in drift speed are recorded as 'irregularities in the Earth's rotation' and 'polar motion'. However, such apparent 'irregularities' and 'motions' require the redistribution of water masses the are 29 times lower.

The sliding of the lithosphere over the asthenosphere is possible in the case when the action duration T is many times longer than the characteristic relaxation time τ within the asthenosphere. It is known that the relaxation time τ is determined from the relationship $\tau = \mu/\eta$, where μ is the viscous coefficient and η is the rigidity. For the asthenosphere, $\mu \approx 10^{18}$–10^{23} P and $\eta \approx 10^{12}$ dyn cm^{-2}. As a result, $\tau = \mu/\eta = 10^{6}$–10^{11} s or 0.03–3000 years. Clearly, the above-mentioned hypothesis could be accepted if we take a lower limit to the permissible values of μ. This hypothesis also agrees with the fact that there is a significant correlation between the seismic activity and the irregularities of the Earth's rotation.

The hypothesis on the drift of the lithosphere over the asthenosphere is based not only on the analysis of the effect of redistribution of water between the ocean and the ice sheets in Antarctica and Greenland but also on a review of the mechanism of the interchange of the angular momentum between the atmosphere and the Earth [8]. The frictional forces and the pressures of the atmosphere and oceans on the lithosphere plates cause their drift along the asthenosphere.

3.2 *The climate variations*

The states of the ice sheets in Antarctica and Greenland depend on the climatic variations. Therefore, the decades-long fluctuations in the Earth's rotation may also correlate with the fluctuations in the climatic characteristics and indices. This relationship has been found in [1].

A close relationship exists between the decades-long fluctuations in the Earth's rotation and the alternation of the epochs of atmospheric circulation, variations in the global air temperature, the regional precipitation and cloudiness, and even changes in the catches of fish in the Pacific Ocean for food [1]. It has been observed that each regime of the Earth's rotation is accompanied by a certain form of atmospheric circulation and, consequently, by certain weather regimes in various parts of the globe. Figure 8 shows the changes in the rotational speed, air temperature in the northern hemisphere, and the accumulated sum of anomalies of the frequency of type C of atmospheric circulation for 1891–1998. Comparing the curves demonstrates their close correlation.

In the seventeenth to nineteenth centuries, there existed the so-called Little Ice Age, while the period of warming has lasted with short intervals since the second half of the nineteenth century up to the present time. It is worth noting that the moments of the sharpest changes in the Earth's rotation rate (about 1870 and 1935) coincide with the end of the Little Ice Age and of the Arctic warming respectively. This close correlation also indicates that the effects of the global water exchange are likely to be responsible for the decades-long variations in the Earth's rotation and the polar motion.

The mechanism of the correlation may be as follows. The water evaporating from the world's oceans precipitates on the ice sheets; then the water returns to the world's oceans mainly through the ice flow. The change in the mass of the ice sheets is mainly determined by the time integral of the difference between the amount of precipitation and the ice flow. The ice flow varies from year to year less than the precipitation does, and to a first approximation

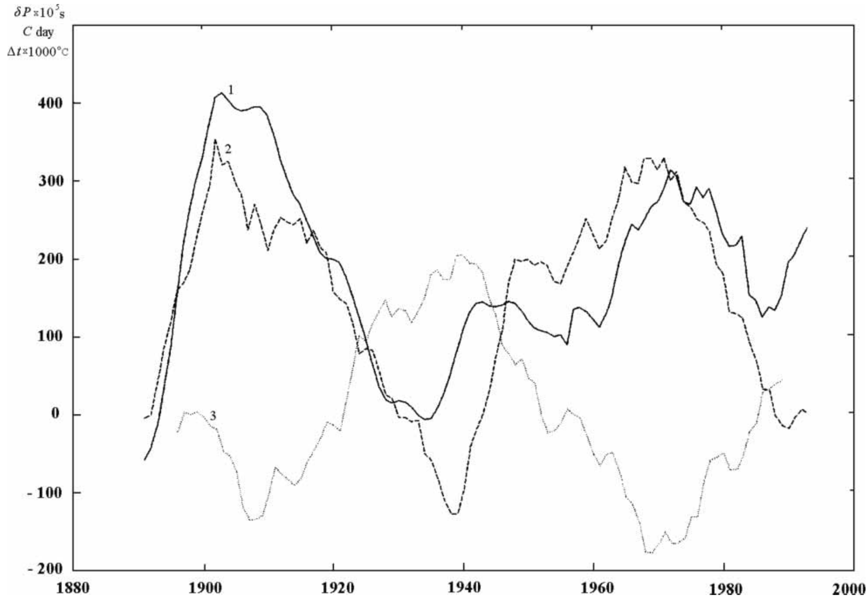

Figure 8. Synchronous changes in the length of the day, δP (curve 1), the cumulative sums of anomalies of the circulation form, C (curve 2), and of the 10 year running anomalies of the northern hemisphere's air temperature, Δt (after elimination of a trend and a thousandfold magnification) (curve 3).

is equal to the precipitation norm. Therefore, the long-term fluctuations in the mass of the ice should approximately coincide with the integral curve of anomalies of the annual sums of precipitation. On the other hand, the precipitation anomalies are dependent on the frequencies of various forms of atmospheric circulation. Therefore, the integral curves of the circulation anomalies can be correlated with the long-term fluctuations in the masses of the ice sheets and ultimately with the instabilities in the Earth rotation. When the masses of the Antarctic and Greenland ice sheets increase, the Earth's polar moment of inertia decreases and the rotation accelerates. The reverse process occurs when the mass of the sheets decreases.

Thus, the atmospheric circulation turns out to be responsible for the variations in the ice masses (including those in the Antarctic and Greenland), because the precipitation and temperature regimes (and eventually the conditions for the formation of the ice sheets) depend on the anomalies in the atmospheric circulation. The manifestation of the anomaly in the atmospheric circulation can also be seen from the behaviours of the anomalies in the wind and pressure fields. Thus, using the global fields of the atmospheric pressure and wind, one can calculate the decades-long fluctuations in the length of the day.

Consequently, the decades-long fluctuations in the rotational speed of the Earth can arise owing to the exchange of angular momentum between the mantle and the liquid core of the planet. Changes in the rotational speed of the liquid core are responsible for fluctuations in the speed of rotation of the mantle. Because of this the total angular momentum of the Earth remains constant. On the other hand, there is a close relationship between the decades-long fluctuations in the Earth's rotation and the changes in climatic and glaciological characteristics. Yet processes in the Earth's core cannot affect the alternation of epochs of atmospheric circulation, air temperature fluctuations, atmospheric precipitation, the state of glaciers, and others climatic processes and characteristics.

The above contradictions can be eliminated by assuming the existence of the third reason, which simultaneously affects both the processes in the Earth's core and in the climatic system. This reason is the gravitational interaction of the Earth with the Moon, the Sun and other planets. In particular, the gravity of the non-spherical non-uniform shells of the Earth (that occupy eccentric positions) due to the Moon, the Sun and planets leads to shifts and fluctuations in the centres of mass of the shells relative to each other, as well as to their forced transitions [9]. The set of phenomena that arise in the Earth's shells can be called generalized tides.

On the one hand, the generalized tides evoke changes in the core and are related to the perennial variations in the geomagnetic field. On the other hand, they are responsible for changes in the climatic system, which lead to fluctuations in the Earth's rotation. In this case, evidently, the decades-long variations in the rotation will correlate with all the above-mentioned geophysical and hydrometeorlogical processes.

Thus, the decades-long fluctuations in the Earth's rotational velocity and the secular polar motion are probably due to the fluctuations in the velocity of the lithosphere drift along the asthenosphere. These fluctuations are due to the variations in the lithosphere's moments of inertia. The latter are associated with the redistribution of the water masses between the world's oceans and the ice sheets of the Antarctic and Greenland. On the one hand, the atmospheric and oceanic circulations are responsible for the redistribution of water on the Earth's surface and, on the other hand, these circulations govern the global climatic conditions. The initial cause of the decades-long fluctuations of the atmospheric and oceanic circulations is probably the gravitational interaction between the Earth's non-spherical and eccentric envelopes and the Moon, the Sun and the planets.

4. Application of data on the Earth's rotation in hydrometeorology

Studying the irregularity of the Earth's rotation is promising for solving the inverse problems. The fact is that it is much more difficult to define the fluctuations in global characteristics of the atmosphere or hydrosphere than the fluctuations in the speed of the Earth's rotation, the latter reflecting the processes in the atmosphere and hydrosphere. Thus, to calculate the wind's angular momentum, it is necessary to collect data on the distribution of the wind with the altitude from every possible aerological station in the world, to perform their objective analysis (interpolation and extrapolation) and to calculate the integral over the volume of the atmosphere. At the same time, data on the seasonal variations in the angular velocity of the Earth's rotation allow one to define easily the fluctuations in the wind's angular momentum with nearly the same accuracy. To do this, it is sufficient to take into account just some known corrections (figure 6).

The seasonal irregularity in the Earth's rotation reflects the functioning of the IHTE and can be used as an indicator of the difference between the temperatures of the northern and southern hemispheres, as well as of the intensity of air circulation and moisture exchange between the hemispheres.

The decades-long fluctuations in the Earth's rotational speed and the secular polar motion are used to computing the changes in the Antarctic and Greenland ice masses and the mass of water in the world's oceans (figure 7). Using the decades-long fluctuations in the Earth's rotational speed, one can observe and, to some extent, predict the climatic variations. The point is that the periods of accelerated rotation of the Earth (decrease in the length of the day) coincide with the epochs of negative anomalies of the frequency of type C and of positive anomalies of the frequency of the combined type $W + E$ of the atmospheric circulation. During these periods, the ice mass in Antarctica increases, the intensity of zonal circulation decreases, the rate of the temperature growth observed in the northern hemisphere increases, positive anomalies of global cloudiness prevail, and catches of fish in the Pacific Ocean for food grow (figure 8). During the periods of decelerated rotation of the Earth, the mass of ice in Antarctica decreases, the rate of global temperature growth slows down, negative anomalies of global cloudiness are observed, and catches of fish in the Pacific Ocean for food decrease.

As noted above, in the last 20 years, the tidal fluctuations in the Earth's rotational speed have been carefully measured. For many years, the present author has conducted synchronous monitoring of the tidal fluctuations in the Earth's rotational speed, of the evolution of synoptic processes in the atmosphere, of the atmospheric circulation regimes and of the time variations in hydrometeorological characteristics. As a result, it was noticed that most of synoptic processes in the atmosphere change synchronously with the tidal variations in the Earth's rotation. Based on the retrospective data, the present author has shown that there is a statistically significant correspondence between the tidal fluctuations in the rotational speed and the changes in the atmospheric synoptic processes.

The natural synoptic periods coincide with the periods of a decrease or increase in the Earth's rotational speed. The lunar and solar tides cause the tidal fluctuations in the Earth's rotation. This means that the alterations in natural synoptic periods are caused by zonal tides. To verify this conclusion, we computed the power spectra of the variation in the angular momentum of the atmosphere, which proved the predominance of the harmonics of zonal tides. Synoptic processes in the atmosphere not only evolve owing to the internal dynamics of the climatic system but also are controlled by the lunar and solar zonal tides. Natural synoptic periods are determined by the fluctuations in tidal forces, and they change each other when the sign of the tidal forces changes. This made it possible to predict (with any earliness) the time intervals of natural synoptic periods by calculating the tidal fluctuations in the Earth's rotational speed. Nikolay Sidorenkov and Parel Sidorenkov recently developed a patented technique entitled 'Method for predicting hydrometeorological characteristics' [10]. Our prediction methodology differs fundamentally from all the methodologies used by weather forecasters. It enables one to make weather forecasts with a daily discreteness for a 1 year period. About 75% of such forecasts proved to be correct.

We believe that this methodology can also be used to predict natural and social phenomena, such as seismicity, volcano eruptions, economic crises, epidemics, population explosions, political coups and even wars. This necessitates the integrated space–time analysis of various events provided that scientists in various domains – medical doctors, psychologists, historians, astronomers and geophysicists – will simultaneously work towards this. In this case it will be feasible not only to identify in retrospect the coincidences and regularities of natural and social cataclysms but also to make probabilistic predictions of such events.

References

[1] N.S. Sidorenkov, *Fizika Nestabilnostey Vrashenija Zemli* (*Physics of the Earth's Rotation Instabilities*) (Nauka, Fizmatlit, Moscow, 2002), p. 384 (in Russian with English summary and contents).
[2] N.S. Sidorenkov, in *Polar Motion: Historical and Scientific Problems*, IAU Colloquium 178, ASP Conference Series, edited by S. Dick, D. McCarthy and B. Luzum (US Naval Observatory, Washington, DC, 2000), pp. 455–462.
[3] K. Lambeck, *The Earth's Variable Rotation* (Cambridge University Press, Cambridge, 1980), p. 449.
[4] W.H. Munk and G.T.F. MacDonald, *The Rotation of the Earth* (Cambridge University Press, London, 1960), p. 323.
[5] E.H. Vestine and A.B. Kahle, Geophys. J. R. Astron. Soc. **15** 29 (1968).
[6] N.S. Sidorenkov, Astron. Zh. **56** 187 (1979) (Engl. transl., Soviet Astron. – AJ **23** 102 (1979)).
[7] V.N. Petrov, *Atmosfernoe Pitanie Lednikovogo Pokrova Antarktidy* (*Atmospheric Nourishment of the Antarctic Ice Sheet*) (Gidrometeoizdat, Leningrad, 1975) (in Russian).
[8] N.S. Sidorenkov, in *Journees 2003, Astrometry, Geodynamics and Solar System Dynamics: from Milliarcseconds to Microarcseconds*, St Petersburg, Russia, 22–25 September 2003, edited by A. Finkelstein and N. Capitaine (Institute of Applied Astronomy of RAS, St. Petersburg, 2003), pp. 225–230.
[9] Yu.V. Barkin, in *Polar Motion: Historical and Scientific Problems*, IAU Colloquium 178, ASP Conference Series, edited by S. Dick, D. McCarthy and B.Luzum (US Naval Observatory, Washington, DC, 2000), pp. 373–379.
[10] N.S. Sidorenkov and P.N. Sidorenkov, Russ. Pat., Russian State Invention Register (10 May 2002).