3RD CONFERENCE OF THE ARABIAN JOURNAL OF GEOSCIENCES (CAJG)
2–5 NOVEMBER 2020, SOUSSE, TUNISIA

Changes of Velocity of Rotation of the Earth, its Figure's Deformation and Long-period Nutational-Precessional Movements of the Instantaneous Pole of Rotation

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Abstract. It is shown, that continuous changes of angular velocity of rotation of the plastically-elastic Earth should cause the continuous coupled deformation of a crustal layer with redistribution of masses in a sub-crustal layer, and also, as consequence of these phenomena, a polar pulsation of figure when polar diameter of the Earth increases and decreases with time. The mechanism of occurrence of deformations of the planet body under action of the deforming (centrifugal) variable force is found, and the equations of balance are deduced. The calculations have given the quite real changes of compression and radial displacements of the Earth's crust and its other shells. The opposite process is also shown, namely: observed fluctuations of amplitude of the polar compression quite correspond to real fluctuations of duration of a day. The influence of the rotational regime on real long-period nutational-precessional motions of the instantaneous pole of the Earth's rotation is considered. The observed 12-month oscillations of the instantaneous axis of rotation are explained by the influence of the variable centrifugal force causing deformation of the figure that is not uniform in different longitudinal zones, without involving the baric-circulational processes as an intermediate link. Thus, both 14-month free (Chandler) and forced 12-month fluctuations of the pole location are considered from a single point of view – as a result of the variability of the rotational regime of the Earth. The analysis of heliogeophysical data for 1900-2017 confirms the validity of the proposed relationship mechanism.

Keywords: Earth Rotation, Deformation of the Earth Figure, Polar Compression, Fluctuations of Angular Velocity, Nutation and Precession, Long-period Pole Movements, Correlation with Heliogeophysical Factors.

1 Introduction

As known, the rotation of the Earth determines its ellipticity, and the shape of the planet (its eccentricity) depends on the angular velocity of rotation, the law of density distribution over depth and latitude [1–3]. In this case, the earth's ellipsoid undergoes conjugate deformation and, as a consequence of the variability of the angular velocity of rotation, polar pulsations of the figure should appear [3]. Due to the uneven distribution of masses in the Earth's body over longitudinal zones, this leads to nutational-precessional oscillations of the Earth's axis or to the movement of the rotation poles [1, 4].

We show, that continuous changes of angular velocity of rotation of the plastically-elastic Earth cause the continuous coupled deformation of a crustal layer with redistribution of masses in a sub-crustal layer, and, consequently, a polar pulsation of figure when polar diameter of the Earth changes with time. We discuss the mechanism of occurrence of deformations of the planet body under action of the centrifugal variable force, and deduce the balance equations. We also show the opposite process when observed fluctuations of amplitude of the polar compression quite correspond to real fluctuations of duration of a day. The influence of the rotational regime on real long-period nutational-precessional motions of the instantaneous pole of the Earth's rotation is also discussed. The observed 12-month oscillations of the instantaneous axis of rotation are explained by the influence of the variable centrifugal force causing deformation of the figure that is not uniform in different longitudinal zones, without involving the baric-circulational processes as an intermediate link. Thus, both 14-month Chandler and forced 12-month fluctuations of the pole location are considered from a single point of view – as a result of the variability of the rotational regime of the Earth. Note that the analysis of heliogeophysical data for 1900-2017 [5] confirms the validity of the proposed relationship mechanism.

2 Earth’s Rotation and its Figure’s Deformation

As known, the rotation of the Earth, characterized by angular velocity, determines its ellipticity, which is the main consequence resulting from the rotation of the figure itself. The shape of the planet − its eccentricity e (or compression α) − depends only on two parameters: the angular velocity of rotation ω and the law of density distribution over depth $d\rho/dr$, as well as, as follows from numerous studies, and latitude ϕ, i.e. $e = F(\omega, d\rho/dr)$ where $d\rho/dr = f(r,\phi)$.

Considering the polar compression of the planets of the Solar System, their angular velocities of rotation and average densities, we can conclude that the degree of compression of a planet mainly depends on its rotation velocity, and therefore, a change of the planet's rotation regime[1] should, first of all, affect the change of polar compression.

From the law of conservation of angular momentum of the Earth, which is written as

$$J\omega = \text{const}, \tag{1}$$

it follows that a change of the angular velocity of the Earth's rotation should inevitably cause a change of the moment of inertia J, $\delta\omega/\omega = -\delta\tau/\tau = -\delta J/J$, where τ and $\delta\tau$ are the length of the day and its change. Moreover, according to the simplest calculations, the change of the moment of inertia corresponding to real changes of the day duration ($\Delta\tau \approx 0.0034\,\text{s}$) should reach

$$\delta J/J = 0.0034/86400 = 4\cdot 10^{-8}\,. \tag{2}$$

According to [8], such a change can occur as a result of a change of the density of the subcrustal layer, its “bulging” (as a result of which deformations arise in the crustal layer). Moreover, according to the calculations given in [8], if we take the thickness of

[1] The question of the reasons for the change of the Earth's rotation velocity is not considered in this paper; the reviews of the hypotheses explaining this phenomenon was published in [1, 6, 7].

the subcrustal layer where the density redistribution takes place, as 80 km, and the thickness of the outer layer that only deforms but does not change its density, as 1 km, then to change the moment the inertia of the Earth corresponding to (2), a vertical displacement of 6-7 m is sufficient.

Note that, as a result of the deformation of the Earth's figure resulting from a change of ω, as it was found in [2, 8, 9], the density redistribution in the subcrustal layer actually occurs. Let ρ_P^0 is the density at the point P in the initial state. After deformation due to radial displacement, the density at point P becomes equal

$$\rho_P = (\rho_P^0 - \zeta\, d\rho_P^0 / dr)(1-\Theta) = \rho_P^0 - \zeta\, d\rho_P^0 / dr - \rho_P^0\, \Theta \qquad (3)$$

where ζ is the displacement, and $\Theta = (1/Q)(dQ/dt)$ where $\Theta = dx\, dy\, dz$ is the volume. In our case (we believe that the Earth is deformed conjugatedly, without changing the volume), $\Theta = 0$ and Eq. (3) takes form $\rho_P = \rho_P^0 - \zeta (d\rho_P^0 / dr)$.

Since ζ is positive, the substance at point P becomes denser (since $d\rho_P^0 / dr < 0$, and therefore $-\zeta\, d\rho_P^0 / dr > 0$). This corresponds to the above noted considerations (see [4]).

The "bulging" of the subcrustal layer should be accompanied by a redistribution of the internal masses (that is, their overflow into this region from the regions in which the negative radial displacement occurs). As known [8], for any internal point P in the initial state, the Poisson equation is written in form $\Delta V_P^0 = -4\pi G \rho_P^0$ where ΔV_P^0 is the Laplacian of gravitational potential V_P in the initial state, G is the gravitational constant. For a deformed state we have $\Delta\, (V_P^0 + V_P) = -4\pi G\, (\rho_P^0 - \zeta\, d\rho_P^0 / dr - \rho_P^0 \Theta)$.

After differentiation, we find $\Delta V_P = 4\pi G\, (\rho_P^0 \Theta + \zeta\, d\rho_P^0 / dr)$ or, if we again assume that the substance of the subcrustal layer is incompressible,

$$\Delta V_P = 4\pi G \zeta (d\rho_P^0 / dr). \qquad (4)$$

Equation (4) shows that when ω decreases, that is, when the deforming centrifugal force is removed, the Earth will return to its original undeformed state due to the occurrence of gravitational effects [given by (4)] caused by the new distribution of masses in the Earth's body. However, it should be noted that the change of density and the redistribution of masses can, by virtue of Eq. (1), affect the change of the angular velocity of the Earth's rotation, that is, the opposite effect can occur (and really occurs).

To find out the effect of the rotation velocity on the change of the shape of the Earth, we consider the relationship of deformations (and displacements) with stresses applied to the volume. For this, as is customary in rheology, we first write down the tensors of the resulting strains and stresses, and then investigate their relationship with each other. As a result, we have obtained the equilibrium equations with three unknowns expressed in terms of displacements (equations of motion in displacements in the Lame form):

$$(\lambda+\mu)\frac{\partial\Theta}{\partial x} + \mu\Delta u + \rho X = \rho\frac{\partial^2 u}{\partial t^2}, \quad (\lambda+\mu)\frac{\partial\Theta}{\partial y} + \mu\Delta v + \rho Y = \rho\frac{\partial^2 v}{\partial t^2},$$
$$(\lambda+\mu)\frac{\partial\Theta}{\partial z} + \mu\Delta w + \rho Z = \rho\frac{\partial^2 w}{\partial t^2}, \qquad (5)$$

where $\Theta = \partial u / \partial x + \partial v / \partial x + \partial w / \partial x$; u, v and w are the displacements; λ and μ are the Lame coefficients; X, Y, and Z are the components of gravitational forces. Equations

(5) express the equilibrium state of the Earth's ellipsoid of revolution, which is under the action of a centrifugal force, and gravitational and surface tension forces, tending to return the Earth to its initial shape, from which, under the influence of a change of centrifugal force (of its increase with growth of ω), it passed to a stressed state.

Solving Eqs. (5) we showed that the Earth ellipsoid is undergoing conjugate deformation at changing the angular velocity of rotation which corresponds to changes of compression really observed by geodetic methods, as well as using satellites (which is 1/298.25±0.02 according to the IUGG/IAG data [10]). Our estimates showed that in the zones of latitudes $\phi = \pm(30-40)^{\circ}$ the radial displacements do not occur with a conjugate change of the figure. Note, that these zones are "belts", where strong earthquakes occur statistically the most frequent, at this, the deformations taking place in the Earth's crust in these belts can generate such precursors of seismic events as the anomalous bursts of the electromagnetic radiation in the ELF-VLF frequency range [11].

3 Movements of the Instantaneous Pole of the Earth's Rotation

As known, the instantaneous axis of the Earth's rotation experiences nutational-precessional oscillations relative to its average position, the main periods are 14-month (the Chandler period) and 12-month (forced variations) ones. In addition, these fluctuations experience significant long-term changes, the causes of which have not yet been fully identified. If for the Chandler variations the fact of their relationship with the unevenness of the Earth's rotation can be considered established (according to the results [12] the correlation between the annual variation of the Earth's rotation period (*T*), on the one hand, and the amplitude (*A*) and the duration of the Chandler's period (*P*), on the other hand, are: $r_{TA} = 0.875$ and $r_{AP} = 0.910$), most researchers consider the 12-month forced variations as a consequence of changes in the global baric circulation regime, putting forward as an argument the observed correlation of pole movements and solar activity (see, for example, [1] and references there). Besides, tectonic hypotheses are used to explain the long-term changes in the forced part of the oscillations of the Earth's instantaneous axis of rotation (see [4] and references there).

We study the role of the Earth's rotation regime in long-term real oscillations of its instantaneous axis of rotation, and also to propose a mechanism that qualitatively explains the observed long-term forced oscillations of the instantaneous axis of rotation due to deformations of the Earth's figure when the angular velocity changes [3]. Basing on an analysis of heliogeophysical data, we show the relationship between real long-period poles' motions and changes of the angular velocity of the Earth's rotation, as well as, basing on the hypothesis of the solar-magnetospheric control of the rotation regime [6, 7], with fluctuations of the Wolf numbers (*W*) and global magnetic disturbance [index $M = 10(\sum K_p - 10)$]. For the elastically deformable Earth, we obtain the relations that relate the period of nutational-precessional pole movements and the deformation of the Earth's body with the angular velocity of rotation. We also represent the results showing the correlation in cycles of different durations of the parameters of free (Chandler) variations of the Earth's rotation pole with changes of heliogeophysical factors, that can be as an indirect confirmation of the hypothesis proposed in [1]. So, we propose a "deformational" mechanism determining the influence of changes of the Earth's rotational movement on the forced part of the nutation-precession oscillations of the rotation axis. Note, that the results of the analysis of heliogeophysical data confirm the validity of the alleged relationships [5].

4 Discussion and Conclusion

In conclusion, it was established that since the angular velocity of the Earth's rotation changes abruptly and continuously, increasing and decreasing on a general tidal background of its damping, the signs of the displacement vectors change passing through zero and, therefore, continuous changes of angular velocity of rotation of the plastic-elastic Earth should cause continuous conjugate deformation of the crustal layer, redistribution of masses in the subcrustal layer and the associated change of density, and also, as a consequence of all these phenomena, the polar pulsation, when the Earth polar diameter increases and decreases. Free 14-month and forced 12-month oscillations of the Earth's instantaneous axis of rotation were considered from a single point of view – as a consequence of the variability of the Earth's rotational regime (due to changes in solar activity indirectly through oscillations global magnetic disturbance). We have attempted to explain the forced part of real variations of the pole's location by the alternating Earth's rotational regime arising due to the polar pulsations of the figure, and also by uneven, along the longitudinal zones, movement of the subcrustal masses in the planetary body. The reality of the movement of subcrustal masses, their "flowing" from the polar regions to the equatorial ones and vice versa, at change of the rotational regime follows from the fact that the substances in the subcrustal layer are in semi-liquid state due to the colossal pressures and temperatures [9]. Further, based on the fact that the density in the Earth's body is nonuniformly distributed, we hypothesized the "deformational" nature of the forced nutational-precessional wave in the oscillations of the instantaneous axis of the Earth's rotation and confirm it by analyzing the heliogeophysical data for 1900-2017 [5].

The main conclusions can be formulated as follows.

1. We have clarified the mechanism of the occurrence of deformations of the planet's body under the action of a time-varying centrifugal force, and based on rheological equations we have derived equilibrium equations and also calculated the modulus of variation of polar compression and radial displacements at real fluctuations of the angular velocity of the Earth's rotation. The results gave quite real changes of compression and radial displacements of the Earth's crust and its underlying shells. The opposite is also shown: the observed fluctuations of the polar compression, leading to corresponding changes of the moment of inertia of the Earth, are consistent with real fluctuations of the day duration.

2. Real fluctuations of the location of the instantaneous pole of rotation occur quite synchronously with fluctuations of the angular velocity of the Earth's rotation, and with some delay relative to the latter, that allows us to put forward the variability of the rotation regime as the cause of long-period precession-nutation movements of the rotation axis.

3. A deforming force arising when the angular velocity changes, causes a deformation of the figure nonuniform over the longitudinal zones. With such a nonuniform deformation, the moment of inertia of the Earth changes, that causes oscillations of its instantaneous axis of rotation, that is, nutation and precession of the axis (forced wave).

4. An analysis of the available factual material confirms the validity of the assumption about the decisive role of changes of the angular velocity both for free 14-month (Chandler) and forced 12-month oscillations of instantaneous rotation axis.

5. The observed correlation of cyclic changes of solar activity, magnetic disturbance, and oscillations of instantaneous axis of the Earth's rotation is explained, taking into account the hypothesis [6, 7], by cyclic changes of the rotation regime, without involving as an intermediate link, the baric circulation processes which have relatively low energy efficiency.

6. It is natural to consider the baric circulation regime changes as a consequence of the variability of the deflecting (Coriolis) force of the Earth's rotation both in magnitude and direction. The Coriolis force vector itself undergoes changes, since the vector of the angular velocity of the Earth's rotation changes in time. Thus, the variability of the rotational regime is put forward as a single reason for the nutational-precessional oscillations of the instantaneous axis of rotation, and it is fundamentally new to consider the variability of the rotational regime as the cause of forced movements of the planet's rotation pole.

Acknowledgments. The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

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