SECULAR EFFECTS IN THE MOTION OF THE EARTH'S CENTER OF MASSES

Yu. V. Barkin
(Sternberg Astronomical Institute, Moscow, Russia)

1. INTRODUCTION

All the processes of Earth's mass redistribution affect the position of its center of masses (ECM). Drift of the ECM is generated by slow (secular) mass redistributions*. Secular effects in the ECM motion can be affected by processes of mass redistribution in the Earth's envelopes, or between them, as well as by global motions and changes of these dynamically nonspherical Earth's envelopes.

The main processes we will refer to are:
(1) sea level change, (2) ice sheet changes (Greenland ice sheet, Antarctic ice sheet) and in general Earth's ice-water envelope change (including glaciers, the ground water and others); (3) tectonic displacements and motion of the crust masses (postglacial rebound, plate motion, subduction and mass accumulation of the dipping oceanic areas of the plates and others); (4) plume and magma motion from the fluid core to the Earth's crust; (5) mantle flows and formation of heterogeneities in the mantle; (6) heterogeneities' motion in the fluid core; (7) slow atmospheric changes due to climatic secular changes.

Other processes we refer to are: (8) global rotation of the lithosphere (and other Earth's envelopes) as an asymmetric body; (9) translatory-rotary motion of the rigid core; (10) displacements of the center of masses of the mantle, fluid core, and other Earth's envelopes. The last three processes define the geological life and history of the Earth.

Thus, the list of the processes and phenomena that characterize and determine slow ECM displacements is long, but the role of each of them can be studied separately. Therefore, in this work we will concentrate on the analysis of the most important processes: ice-water mass redistributions and apparently the slowest processes of tectonic-mass redistribution, namely we will consider the eventual role of subduction and accumulation of masses of submerging oceanic plates.

All the above processes are not infrequently in mutual counteraction, their action variously manifests in different geological epochs, sometimes they compensate one another.

2. SECULAR EFFECTS CAUSED BY ICE-WATER MASSES REDISTRIBUTIONS IN THE PRESENT EPOCH

Let us first make some preliminary estimates of the parameters of the ECM drift due to changes of the sea level and ice sheets of Greenland and Antarctic in the present epoch. In previous papers on the given problem (Farell and Clark, 1976; Wu and Peltier, 1984) some effects of the ice melting of Greenland and Fennoscandia have been studied. Elastic and viscous-elastic Earth's models have been considered in these papers.

Monthly mean sea level observations at 655 tide gauge stations distributed worldwide indicate that the eustatic sea level has been rising at a rate of $\dot{\zeta}_0 = 1.15 \pm 0.38$ mm/yr during the last 80 years (Nakiboglu and Pointon, 1986). This indicates that the volume of ocean water has been increasing by 420 km^3/yr during this period of time.

* In principle, the slow change in the center of mass position can be generated also by quick visco-elastic deformations of the Earth's envelopes, for example, due to lunar-solar tides.

The present mass balance estimates of Greenland and Antarctic ice sheets indicate no melting but an ongoing accretion at respective rates of $\dot{z}_G$ = (2±8) cm/yr and $\dot{z}_A$ = (2±2) cm/yr. The corresponding changes in eustatic sea level are $\dot{\zeta}_G$ = (–0.1±0.4) mm/yr and $\dot{\zeta}_A$ = (–0.6±0.6) mm/yr due to Greenland and Antarctic ice accumulation respectively (Koomanoff, 1985). Significant errors of the above characteristics of course do not allow us to say with confidence about a real ice-water balance.

It is recognized that one of the plausible causes of the observed eustatic rise of the ocean level is the secular warming of climate. The global surface air temperatures have increased by about 0.4°C during the past century (Gornitz et al, 1982). Eustatic rate of the sea level change induced by thermal expansion is estimated as $\dot{\zeta}_W$ = 0.8 mm/yr (Meier, 1984). Although there are some alternative views of the problem, according to which thermal expansion of the ocean is not the principal contribution to the sea level change (Singer, 1997).

One of the major contributions to the sea level rise comes from melting glaciers. This process leads to a sea level rise at a rate of $\dot{\zeta}_{GL}$ = 0.40 mm/yr.

In our paper we will use the simplest model for processes of transformation and redistribution of the ice-water masses of the Earth. We will consider homogeneous and eustatic changes of the sea level and ice sheets ongoing on the rigid surface of the Earth.

Obviously, in the southern hemisphere of the Earth the ocean occupies larger areas. It means that as the sea level is rising the ECM will move southward. Accretion of the Antarctic ice sheet produces a similar effect on the ECM motion. Accretion of the ice masses of the Greenland sheet will partially compensate the above effect.

Thus, the rate of the sea level change is

$$\dot{\zeta} = \dot{\zeta}_G + \dot{\zeta}_A + \dot{\zeta}_W + \dot{\zeta}_{GL} \tag{1}$$

In accordance with what was said, in this paper we will use the following numerical values of the corresponding components of the sea level change:

$$\begin{aligned} &\dot{\zeta} = 1.15\frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_W = 0.80\frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_{GL} = 0.40\frac{\text{mm}}{\text{yr}} \\ &\dot{\zeta}_A = -0.04\frac{\text{mm}}{\text{yr}}, \quad \dot{\zeta}_G = -0.01\frac{\text{mm}}{\text{yr}} \end{aligned} \tag{2}$$

Values of $\dot{\zeta}_A$ and $\dot{\zeta}_G$ in (2) were obtained from the balance equation of the ice-water masses of the Earth.

Data (2) mean that the actual accumulation of the ocean masses is characterized by a rate of $\dot{z}_0$ = 0.35 mm/yr. Accretion rates of the Antarctic and Greenland sheets are $\dot{z}_A$=1.26 mm/yr and $\dot{z}_G$ = 1.69 mm/yr, respectively. Average rate of decrease of the glaciers and ground water is adopted here to be $\dot{z}_{GL}$ = –1.11 mm/yr.

For a thin spherical layer of uniformly accreted masses (ice or water) with density ρ_σ on a certain Earth's surface σ, the components of the ECM velocity in the Earth's reference system of a given epoch are defined by the following surface integrals:

$$\dot{x}_C = \frac{\rho_\sigma R^3}{m}\dot{z}_\sigma \oiint_\sigma \cos^2\varphi \cos\lambda \, d\varphi \, d\lambda$$

$$\dot{y}_C = \frac{\rho_\sigma R^3}{m}\dot{z}_\sigma \oiint_\sigma \cos^2\varphi \sin\lambda \, d\varphi \, d\lambda \qquad (3)$$

$$\dot{z}_C = \frac{\rho_\sigma R^3}{m}\dot{z}_\sigma \oiint_\sigma \cos\varphi \sin\varphi d\varphi$$

Here φ, λ are spherical coordinates of the elementary surface elements $d\sigma$ (φ is latitude, λ is longitude), m and R are mass and radius of the Earth, $\dot{z}_\sigma$ is rate of mass accretion of the corresponding thin growing layer. Integration in (3) is extended to the surface occupied by sea or corresponding ice sheets.

When calculating integrals (3), the real particularities of the surface σ boundaries were taken into account. As a result, we obtained the following general formulae for the components of the ECM velocity (3) (w.r.t. geocentric Greenwich reference system of the given epoch):

$$\dot{x}_C = -0.02929\dot{z}_0 + 0.00049\dot{z}_G - 0.00031\dot{z}_A + 0.02911\dot{z}_{GL}$$

$$\dot{y}_C = -0.02948\dot{z}_0 - 0.00044\dot{z}_G + 0.00075\dot{z}_A + 0.02917\dot{z}_{GL} \qquad (4)$$

$$\dot{z}_C = -0.03700\dot{z}_0 + 0.00222\dot{z}_G - 0.01258\dot{z}_A + 0.04736\dot{z}_{GL}$$

We emphasize that the parameters in (4) characterize real secular growing or decay of the masses along the corresponding surface σ. Using the above values for these parameters, with equation (4) we obtain the following conclusion.

1. Due to ice-water masses' redistribution of the Earth, glacier melting, growth of the Antarctic and Greenland ice sheets, and mass accumulation in the sea, the center of masses of the Earth is moving at a velocity of 0.49 cm/cy in the direction SE.

It is worth noting that the derived velocity is very sensitive to the model parameters. Taking into account a big spread in values of components (2) of the rate of the sea level rise as given by different authors (Meier, 1984; Nakiboglu and Pointon, 1986; Whar et. al., 1993; Singer, 1997), our estimates should be considered as crude and preliminary or as some numerical examples.

With more certainty we can say about directions of the ECM displacements due to each of the mechanisms considered separately. Using formulae (4) and values (2), we come to the following conclusions.

1.1. Due to growth of the ocean masses at a rate of $\dot{z}_0 = 0.35$ mm/yr, the ECM is moving toward the geographic point 41°.7 S, 134°.8 E (in the south of the Pacific Ocean) at a velocity of 1.95 mm/cy.

1.2. Due to accretion of the ice masses of the Greenland sheet at a rate of $\dot{z}_G = 1.69$ mm/yr, the ECM is moving at a velocity of 0.39 mm/cy in the direction 73°.0 N, 40°.1 W (toward the island center).

1.3. Due to accretion of the ice masses of the Antarctic sheet at a rate of $\dot{z}_A = 1.76$ mm/yr, the ECM is moving at a velocity of 1.59 mm/cy in the direction 86°.3 S, 112°.4 W (toward the Antarctic center).

3. ON THE DISPLACEMENT OF THE EARTH'S CENTER OF MASSES IN THE POSTGLACIAL PERIOD

Here, on the basis of the simplest transformation model of the northern and southern ice caps of the Earth and corresponding rise of the sea level in the last postglacial period, some possible effects in the ECM motion are studied.

The latest postglacial epoch began about 8,000 years ago. It was preceded by the last glaciation (115,000 years ago to 10,000 years ago). The maximum of glaciation was about 18,000 years ago and ended about 8,000 years ago.

The known data about redistribution of the ice masses in these epochs and character of sea level variation allow us to estimate the parameters of the ECM displacement due to melting of glaciers and sea level change on the basis of the results obtained in section 2 [formula (4)]. In this paper, we will consider only the 10,000-year period (t_0, t) of intensive sea level change which follows immediately after the period of maximal glaciation (t_0) to the epoch of the beginning of the new postglacial period (t). During this period, the sea level rose by 125–130 meters; this was established and confirmed by different methods (geological and isotopic) (Barkov et al., 1997). The mean rate of sea level rise in this period was quite considerable and constituted $\dot{z}_0 = 12.5$ mm/yr. It is much greater than the modern value of $\dot{z}_0$.

We will use the known data about distribution and structure of the ice masses of the Pleistocene ice sheet (Donn et. al., 1962; O'Connell, 1971, and others).

According to these data, the ice volumes of Greenland and Antarctic sheets (or of the northern and southern ice caps of the Earth) at epoch t_0 are estimated as $65 \cdot 10^6$ km^3 and $35 \cdot 10^6$ km^3. At the present epoch (t), the volumes of these sheets constitute $3 \cdot 10^6$ km^3 and $27 \cdot 10^6$ km^3 respectively.

Taking an ice density of $\rho = 0.92$ g/cm^3, we express the masses of the northern and southern ice caps of the Earth in units of the Earth's mass $m = 0.597 \cdot 10^{28}$ g. For the two epochs considered, we have:

$$m_A^0 = 0.54 \cdot 10^{-5}\, m, \qquad m_A = 0.42 \cdot 10^{-5}\, m,$$
$$m_G^0 = 1.00 \cdot 10^{-5}\, m, \qquad m_G = 0.05 \cdot 10^{-5}\, m. \tag{5}$$

To solve the problem of the ECM displacement, we must know not only the change of the ice sheets' masses, but also the change of the positions of their centers of masses. To determine these positions, we use the following simplest model of the ice caps and some additional simplified assumptions: (i) each of the caps is a thin spherical segment with homogeneous ice distribution (a similar model was considered by Whar et. al., 1993); (ii) the segment boundary is circular, and angular distance from segment center is characterized by angle α; (iii) during the period (t_0, t), centers of the ice caps had negligible displacements, and their positions correspond to the present-day positions of the ice sheets (86°.3 S, 112°.5 E for the southern cap and 73°.5 N, 47°.9 W for the northern cap); (iv) angular sizes of the northern and southern caps α are 40° and 30° (for epoch t_0), 10° and 20° (for present epoch t); (v) ice masses are characterized by homogenous distribution and by masses (5); (vi) processes of the melting and rise of the sea level are eustatic and uniform.

The distance between the cap center and geocenter is

$$r_\sigma = \frac{1}{2} R(1 - \cos\alpha_\sigma), \tag{6}$$

where R is the Earth's radius and α_σ is angular size of the cap. Displacement (6) is directed toward the center of the corresponding spherical segment occupied by the cap [see (ii)].

For the adopted model values from (iv), using formula (6), we found the values of the radial coordinates of the caps' centers of mass at epochs t_0 and t:

$$r_G^0 = 5600 \text{ km}, \qquad r_A^0 = 5900 \text{ km},$$
$$r_G = 6300 \text{ km}, \qquad r_A = 6200 \text{ km}, \tag{7}$$

Coordinates of the cap centers and values (7) completely determine the radii-vectors of the ice cap centers $\bar{r}_G^0, \bar{r}_A^0$ and $\bar{r}_G, \bar{r}_A$ at epochs t_0 and t, respectively.

Masses (5) and coordinates (7) allow us to estimate a change of the static moment of the ice masses. Change of the static moment of the ocean masses, grown during the period (t_0, t) at a mean rate of $\dot{z}_0 = 12.5$ mm/yr, in accordance with section 2, will be:

$$\bar{S}_0 = m \begin{pmatrix} -0.02929 \\ -0.02948 \\ -0.03700 \end{pmatrix} z_0,$$

where $z_0 = 125$ m.

Displacement vector $\bar{r}$ of the ECM during the period of time (t_0, t), due to the considered redistribution of the ice-water masses is determined from the equation of conservation of the static moment of the Earth's masses:

$$m_A^0 \bar{r}_A^0 + m_G^0 \bar{r}_G = m_A \bar{r}_A + m_G \bar{r}_G + \bar{S}_0 + m\bar{r}. \quad (8)$$

Equation (8) allows us to find displacements of the ECM and corresponding mean rates in the period (t_0, t) for each of the processes considered and their full effect. We come to the following final conclusions.

1. Due to melting of the northern ice cap in the first 10,000 years after the maximum of the last glaciation, the ECM has moved by 53 meters southward in the direction of the geographic point 73°.5 S, 138°.1 E. The mean rate of this displacement was 5.3 mm/yr.

2. Due to melting of Antarctic ice in period (t_0, t), the ECM has moved by 6.3 meters from its initial position northward in the direction 86°.3 N, 292°.5 E. The rate of this displacement was 0.63 mm/yr.

3. Due to ice transformation to oceanic masses and increasing of the sea level on 125 meters in period (t_0, t), the ECM has moved by 7.0 meters in the direction 41°.7 S, 225°.2 E. The rate of this displacement was 0.70 mm/yr.

4. Under the action of all the above-mentioned mechanisms of transformation and redistribution of the ice-water masses of the Earth during the period of time (t_0, t), the ECM has moved by 52 meters in the direction of the geographical point 72°.1 S, 157°.7 E. The mean rate of the displacement was 5.2 mm/yr.

These estimates show that during certain periods of the Earth's history, particularly in periods of fast and catastrophic changes of its dynamical structure, the effects of displacements of the ECM may be quite significant.

On the other hand, variations of the ECM position must lead to some dynamical effects in relative motions of the Earth's envelopes due to change of their positions with respect to the Earth's axis of rotation. In this connection, a further study of the ECM displacements at different timescales is a very important task.

The above estimates were obtained for the rigid model of the Earth crust. Visco-elastic properties of the crust and other accompanying redistributions of the Earth's masses will lead to some corrections of these displacements. These corrections can be studied separately using the well-known approach (Nakiboglu and Pointon, 1986; O'Connell, 1971; Wu and Peltier, 1984). Here we do not consider these effects, taking into account our crude model.

Periods of glaciations are cyclic. They are repeated every 100,000 years. It is known that sea level "serrately" changes in accordance with this process. The above-obtained results directly show that change of the direction of the glaciation process will reverse the direction of the ECM displacement. According to these simplified concepts and models, during a glacial period the ECM tends to move northward, and after periods of maximum glaciation the ECM tends to move southward.

Displacements of the ECM lead to a change in the positions of the centers of masses of the mantle, fluid core, and rigid core with respect to the Earth's rotation axis. It means that in the relative motions of these structures there must be certain dynamic effects (variations of their relative rotations, etc.).

4. SUBDUCTION OF PLATES AND THE DRIFT OF THE EARTH'S CENTER OF MASSES

4.1. Variations of the coefficients of the first and second harmonics of the geopotential

Let us now investigate the effect of global tectonic motions on the displacement (drift) of the ECM, namely the influence of the motion of plates, their subduction and accumulation of masses of the submerging oceanic plates along the subduction zones. The role and contributions of other geodynamic processes to the ECM motion can be studied separately. The aim of this work is to estimate the parameters of the ECM drift at the modern geological epoch.

One of the main regularities, found by the method of seismic tomography, is the presence of excess masses along the subduction zones at depths of 350–550 km. The excess of masses in the subduction zones is caused by the relatively cool matter of the oceanic lithosphere, pushed under the volcanic arcs; this cool matter forces the hot mantle matter of the arcs upward (Hain and Zverev, 1991). The global structures, revealed in the mantle by the method of seismic tomography, are associated with the accumulation of the oceanic-plate blocs, submerging along the subduction zones. The ring of the regions with increased seismic velocities, surrounding the Pacific Ocean, is due to subduction and accumulation of masses at depths of about 1000 km. It is noted that this process has been taking place during the last 200 millions of years (Dziewonski and Ekstrem, 1996).

The process of formation of inhomogeneities is dynamic; it is lasting at geological time intervals. For this reason alone, the excess masses cannot get a complete isostatic compensation, especially under the conditions, where the rotation axis is changing its position in the Earth's body. All the nonspherical, unbalanced Earth's envelopes interact in a complex manner; this interaction inevitably results in their relative displacements. The excess masses along the subduction zones have been accumulating there at a certain rate during millions of years. Certainly, this must have a reflection in variations of the geopotential coefficients, Earth's rotation, and ECM position.

We proposed two methods of determination of the components of the Earth's tensor of inertia, caused by the mechanism of subduction and accumulation of masses. One of the mechanisms is basing on the analytical description of "the effect of overlap of plates" along the subduction zones; it is based on the kinematic theory of the absolute motion of plates (Barkin, 1995a, 1996). The other method – a more direct one – uses the procedure of analysis of mass inflow rate over all the subduction zones and determination of the corresponding variations of the components of the tensor of inertia (Barkin, 1996). This procedure is reduced to calculation of volume integrals over the subduction zones. In this case, we use the well-known data on the thickness of the submerging lithosphere ($H = 80$ km), its mean density ($\rho = 3.3$ g/cm^3) as well as the parameters of the kinematic theory of the relative motion of plates (Ushakov and Galushkin, 1978).

We will call the fraction of the accumulated masses in the total masses, submerging in the subduction zones, the coefficient of the mass accumulation intensity i_a. We estimated this parameter, in particular, by an analysis of the parameters of the model of the nonuniform, nonspherical Earth's envelopes and envelopes of its inhomogeneities (Barkin, 1997); we also used data on the features of the global tectonic process during the last 43 million years. As a result, we established that a fraction $i_a = 1/3$ of the total mass of oceanic plates, inflowing to the subduction zones, is subject to accumulation.

Variations of the coefficients of the first and second geopotential harmonics, calculated with the above rate of accumulation of the oceanic-plate masses, are:

$$\begin{aligned}
\dot{C}_{10} &= 0.336\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{C}_{11} &= -1.257\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{S}_{11} &= 0.278\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{J}_{2} &= 0.648\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{C}_{21} &= -0.290\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{S}_{21} &= 0.433\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{C}_{22} &= -0.174\cdot 10^{-9}\ \text{century}^{-1},\\
\dot{S}_{22} &= -0.321\cdot 10^{-9}\ \text{century}^{-1},
\end{aligned} \tag{9}$$

4.2. Paleomigration of the Earth's pole

Dynamic investigations show that secular motion of the Earth's rotation axis pole P_ω is due to redistribution of masses in the deformable Earth, which lead to variations of the Earth's products of inertia or of the corresponding geopotential coefficients C_{21}, S_{21}. We will use the results of an analytical description of secular effects in the rotational motion of a celestial body with a deformable outer envelope (Barkin, 1996). The motion of the pole with velocities (1) is referred to the main central axes of inertia of the body for the given epoch $Cx_0y_0z_0$. The vector of angular velocity $\vec{\omega}$ describes the rotation of precisely this system of coordinates. Variations $\dot{C}_{21}, \dot{S}_{21}$ are determined with respect to the system of coordinates $Cx_0y_0z_0$, too.

The main components of the pole drift velocity P_ω in coordinate axes Cx_0, Cy_0 are given by the following simple formulae:

$$\dot{p} = \omega\left(\frac{\omega}{\Omega}+1\right)\frac{\dot{C}_{21}}{I}, \quad \dot{q} = \omega\left(\frac{\omega}{\Omega}+1\right)\frac{\dot{S}_{21}}{I}.$$

Here ω and Ω are the frequencies of the unperturbed Chandler motion of the body, $\omega+\Omega$ is the rate of the Earth's diurnal rotation, $I=\dfrac{C}{mR^2}$ is the dimensionless moment of inertia (C, m and R are the polar moment of inertia, mass, and mean radius of the deformable body, respectively), $\dot{C}_{21}, \dot{S}_{21}$ are secular variations of geopotential coefficients C_{21}, S_{21}.

Thus, owing to a slow rebuilding of the body's dynamic structure, the pole of the rotation axis P_ω is moving at angular velocity ν_ω along meridian λ_ω, where

$$\nu_\omega = \left(\frac{\omega}{\Omega}+1\right)\frac{\sqrt{\dot{C}_{21}^2+\dot{S}_{21}^2}}{I}, \quad \lambda_\omega = \arctan\left(\frac{\dot{C}_{21}}{\dot{S}_{21}}\right). \tag{10}$$

The Earth's dynamic structure is close to that of an axisymmetric body; therefore, formulae (10) conserve their form if we use the Greenwich system of coordinates as the main one. In this case, λ_ω is the Greenwich longitude, and variations $\dot{C}_{21}, \dot{S}_{21}$ are also defined in the Greenwich system of coordinates.

For the values of $\dot{C}_{21}, \dot{S}_{21}$ from (9), we find with (10) that the pole of the Earth's rotation axis is moving at velocity $\nu_\omega = 0^\circ.40$ Myear^{-1} along the meridian $\lambda_\omega = 56^\circ.2$ W. The parameters found are in a good agreement with their "observed" values for the Earth's pole, obtained by the paleomagnetic methods (Sabadini and Yuen, 1989):

$$\nu_\omega = 0^\circ.56\ \text{Myear}^{-1}, \quad \lambda_\omega = 40^\circ\text{W}.$$

Thus, the main cause of the Earth's pole paleomigration is the global tectonic process and the accompanying geodynamic processes of subduction and accumulation of masses of the oceanic plates. For the value we have found for the coefficient of the mass accumulation rate, the pole paleomigration at the present epoch gets a full explanation, in both magnitude and direction.

Richards and Hager (1984), Hager et al. (1985) developed another approach to the explanation of the drift of the Earth's axis pole; in these works, the clue role belongs to the mechanism of mantle convection, taking into account the presence of heterogeneities in the mantle, peculiarities of plate geometry and motions, their subduction, etc. The model, proposed in this work, is simpler and, seemingly, more feasible from the mechanical point of view. It has allowed us to estimate secular variations of the geopotential coefficients (the first and second harmonics) and, in particular, to reveal a new fundamental phenomenon in geodynamics – secular drift of the Earth's center of masses.

4.3. Variation of J_2

The value of variations of coefficient J_2 of the geopotential, obtained on the basis of laser observations of the Earth's satellites during the last 20 years, is estimated as $\dot{J}_2 = (-2.7\pm0.4)\cdot10^{-9}$ cy^{-1} (Yoder et. al., 1983; Cheng et. al., 1997).

On the other hand, interpretation of variation $\dot{J}_2$ due to postglacial situation yields a greater value $\dot{J}_2 = (-3.2\pm0.3)\cdot10^{-9}$ cy^{-1} (Yoder, 1998).

Thus, the "observed" discrepancy $\Delta\dot{J}_2 = 0.5\cdot10^{-9}$ cy^{-1} can be explained by this additional "tectonic" variation from (9) $\dot{J}_2 = 0.65\cdot10^{-9}$ cy^{-1}.

4.4. Secular drift of the Earth center of masses

For the above-mentioned mechanism of change of the Earth's dynamical structure, the variations of the first harmonic coefficients of the geopotential were determined. The corresponding components of the velocity of the secular drift of the ECM are:

$$\dot{x}_C = -0.801 \text{ cm/cy}, \quad \dot{y}_C = 0.177 \text{ cm/cy}, \quad \dot{z}_C = 0.214 \text{ cm/cy}.$$

Due to formation of heterogeneiteis and excess masses in the regions of the subduction zones, the ECM moves about its position in the given epoch at a velocity of 0.47 cm/cy in the direction of the geographic point 14°.6 N, 167°.6 E. This direction correlates with the direction from geocenter to magnetic center of the Earth (15°.1 N, 150° E) and with the direction of vector of the momentum of the lithosphere plates' motion according to the NNR-NUVEL1 theory (Barkin, 1996). Displacement of the ECM corresponds to relative displacement of the centers of mass of the fluid core and mantle. It is a significant evidence that the nature of the eccentricity of the Earth's magnetic field is connected with the excentricity of the center of masses of the fluid core w.r.t. the Earth's axis of rotation.

The secular effects in the ECM motion are probably too small to be detected by current satellite observations (Montag et. al., 1995). However, some other secular or long-period variations of the ECM position can take place, for example, due to displacements and motion of the rigid core (Barkin, 1997). In this connection, experimental determination of the parameters of the ECM drift is an important problem.

5. CONCLUSION

The estimates obtained of the ECM secular motion parameters due to redistribution of the ice-water masses in the present and postglacial epochs are preliminary. They were obtained for the simplest models of the transformation and redistribution of the masses. We have used these models because of big errors in the parameter values characterizing these processes. In future we will consider the role of the elastic and visco-elastic properties of the Earth, following the known approaches (Wu and Peltier, 1984; Nakiboglu and Pointon, 1986; O'Connell, 1971, and others).

The global tectonic process (subduction, mass accumulation processes and others) gives a significant contribution to the observed Earth's pole drift (practically, this process explains paleomigration of the pole w.r.t. mantle reference system), and to variation $\dot{J}_2$ (it explains the "observed" discrepancy $\Delta\dot{J}_2$). This global process also determines the slow drift of the ECM. The last effect reflects the eccentricity of the center-of-mass positions of the fluid core, mantle, and other Earth's envelopes. Displacements of the centers of massess of these envelopes, caused by Earth's mass redistribution and by mutual interactions, manifest themselves at geological time intervals and have an important significance for the geodynamic history and evolution of the Earth..

6. ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Reaserach (project code 96-05-65015) and a grant of the Program of fundamental studies "Universities of Russia".

References

Argus, D. F. and Gordon, R.G., 1991, "No-not-rotation model of current plate velocities incorporating plate motion model NUVEL-1," *Geophys. Res. Lett.*, **18**, pp. 2039–2042.

Barkin, Yu.V., 1996, "Secular variation due to subduction of the plates," in *Earth Rotation Reference Systems in Geodynamics and Solar System* (Proc. of the Internat. Conf., Warsaw, Poland, September 18–20, 1995). Journées 1995, SRC, PAS, Warsaw, Poland, pp.159–160.

Barkin, Yu. V., 1995, "Lithosphere plate motion as a mechanism of secular variations of the geopotential coefficients and Earth's rotation", *Vestnik Mosk. Gos. univ.., Ser. 3, Phys., astron.*, **36**, No. 6, pp. 89–94 (in Russian).

Barkin, Yu. V., 1996, "Secular drift of the Earth's center of masses, caused by the plate motion," *Vestnik Mosk. Gos. univ.., Ser. 3, Phys., astron.*, **37**, No. 1, pp. 79–85 (in Russian).

Barkin, Yu. V., 1997, "Secular effects in the geocenter motion," *EOS Trans. AGU,* **78(46)**, Fall Meet. Suppl., p. F 145.

Barkin, Yu. V., 1998, "Global properties of the structure, evolution, and interconnections of the lithosphere and other envelopes of the Earth," in *Interaction in the Lithosphere–Hydrosphere-Atmosphere System,* (Proc. of the Conf., Moscow, November 28–29, 1996) (in Russian).

Barkov, N. I. , Danilov, A.I., *et al.*, 1997, "Paleoclimatic cycles as determined by ice kerns from a deep well at the Vostok station and by columns of lake deposits of the Banger oasis (Antarctica)," in *Earth Sciences on the Eve of the 21st Century* (Abstracts of papers of the Conf., Moscow, November 11–14, 1997), Nauchnyj Mir, Moscow, p. 22 (in Russian).

Chebanenko, I. I. and Fedorin, Ya. V., "On the variation of the Earth's polar oblateness and its temporal relation to geotectonic cycles in the Phanerozoic era," *Doklady Akad. Nauk SSSR*, **274**, No. 4, pp. 907–909 (in Russian).

Cheng, M. K., Shum, C. K., and Tapley, B. D., 1997, *J. Geophys. Res.*, **102**, No. B10, pp. 22,377–22,390.

Donn, W. L., Ferrand, W. R., and Ewing, M., 1962, "Pleistocene ice volumes and sea level lowering ," *J. Geol.*, **70**, pp. 206-214.

Dziewonski, A.M., Ekstrom, G., 1996, "Seismic tomography and plate tectonics," in *XXI General Assembly of EGS (the Hague, May 6-10, 1996), Annales Geophysicae*, Supplement 1 to Volume 14, Part I, p. C31.

Etkins, R. and Epstein, E. S., 1982, "The Rise of Global Mean Sea Level as an Indication of Climatic Change," *Science*, **215**, pp. 287–289.

Farell, W. E. and Clark, J. A., 1976, "On Postglacial Sea Level," *Geophys. J. R. Astr. Soc.*, 46, pp. 647–667.

Gordon, R. G., 1995, "Plate motions, crustal and lithospheric mobility, and paleomagnetism: Prospective viewpoint," *J. Geophys. Res.*, **100**, pp. 24,367–24,392.

Gordon, R. G. and Livermore, R. A., 1987, "Apparent polar wander of the mean-lithosphere reference frame," *Geophys. J. R. Astron. Soc.*, **91**, p. 1049–1057.

Gornitz, V. *et. al.*, 1982, "Global Sea Level Trend in the Past Century," *Science*, **1**, pp.1611-1614.

Hager, B. H., Clayton, R. W., Richards, M. A., Comer, R. P., and Dziewonski, A. M., 1985, "Lower mantle heterogeneity, dynamic topography and the geoid," *Nature*, **313**, pp. 541–545.

Hain, V. E. and Zverev, A. T., 1991, "A geodynamic analysis of topographic maps," *Doklady Akad. Nauk SSSR*, pp. 221–225 (in Russian).

Koomanof, F. A. (ed), 1985, *Glacier, Ice Sheets, and Sea Level Effect of a CO-Induced Climatic Change,* National Technical Information Service, U. S. Department of Commerce, Springfield, Va.

Meier, M., 1984, "Contribution of small glacier to global sea level," *Science*, **226**, pp. 1418–1421.

Montag, H., Gendt, G., Reigbar, Ch., and Wilson, P. 1995, "Some Remarks on the Determination of the Terrestrial Reference Frame by Different Techniques," *Paper presented to the XXI General Assembly of the IUGG, Boulder, Colorado, U. S. A., July 2–14, 1995,* Geo Forschungs Zentrum, Potsdam.

Nakiboglu, S.M. and Pointon, K. W., 1986, "Rotational Response of the Earth to Ongoing Sea Level Changes," in *Proc. Int. Symp. Figure and Dynamics of the Earth, Moon and Planets,* Prague, Part II, pp. 525–542.

O'Connell, R. J., 1971, "Pleistocene glaciation and viscosity of the lower mantle," *Geophys. J. R. Astr. Soc.*, **23**, pp. 299–327.

Richards, M. and Hager B., 1984, "Geoid anomalies in dynamic Earth," *J. Geophys. Res.*, **89**, pp. 5987–6002.

Richards, M.A., Ricard, Y., Lithgow-Bertelloni, C., Spada, G., and Sabadini R., 1997, "An explanation for Earth's long-term rotational stability," *Science*, **275**, pp. 372–375.

Sabadini, R. and Yuen, D.A., 1989, "Mantle stratification and long-term polar wander," *Nature*, **339**, pp. 373-375.

Singer , 1997, "Will Global Warming Really Raise Sea Level?" *EOS Trans. AGU,* **78(46)**, Fall Meet. Suppl., p. F 273.

Stienberger, B. and O'Connell, R.J., 1997, "Changes of the Earth's rotation axis owing to advection of mantle density heterogeneities," *Nature*, **387**, pp. 169–173.

Ushakov, S. A. and Galushkin, Yu. I., 1978, "The Earth's Lithosphere. 4.1. Plate Kinematics and Oceanic Lithosphere", in *Physics of the Earth,* V. V. Fedynskij and K. S. Losev (eds), VINITI, Moscow, vol. **3**, p. 272 (in Russian).

Wahr, J., Dazhong, H., Trupin, A., and Lindqvist, V., 1993, "Secular changes in rotation and gravity: evidence of post -glacial rebound or of changes in polar ice?" In *Advances in Space Res.,* **13**, No. **11**. Observations of Earth from Space. R. P. Singh, V. Feissel, B. D. Tapley, C. K. Shum (eds), Pergamon Press, Oxford, New York, Seoul, Tokyo.

Wu, P. and Peltier, W. R., 1984, "Pleistocene Deglaciation and the Earth's Rotation: a New Analysis," *Geophys. J. Roy. Astr. Soc.*, **76**, pp. 753–791.

Yoder, C.F., 1998, "Contributions to present-day polar motion, J_2 and UT1 changes," *XXIII General Assembly of EGS (Nice, April 20-24, 1998). Annales Geophysicae*, Supplement I to Volume 14, Part I, p. C58.

Yoder, C. F., Williams, J. G., Dickey, J. O., Schutz, B. E., Eanes, R. J., and Tapley, B. D., 1983, "Secular variation of Earth's gravitational harmonic J_2 coefficient from Lageos and nontidal acceleration of Earth rotation," *Nature*, **303**, pp. 757–762.