ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2017, Vol. 53, No. 4, pp. 565–580. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © V.V. Adushkin, S.A. Riabova, A.A. Spivak, 2017, published in Fizika Zemli, 2017, No. 4, pp. 76–92.

Lunar–Solar Tide Effects in the Earth's Crust and Atmosphere

V. V. Adushkin, S. A. Riabova, and A. A. Spivak*

Institute of Geosphere Dynamics, Russian Academy of Sciences, Moscow, Russia

**e-mail: spivak@idg.chph.ras.ru*

Received December 5, 2016

Abstract—The gravitational interaction in the Earth–Moon–Sun system is considered from the standpoint of influencing the formation of time variations in the geophysical fields and some natural processes. The analysis of the results of instrumental observations revealed the main periodicities and cycles in the time variations of subsoil radon volumetric activity with the same periods as the vertical component of the variations of the tidal force. The amplitude modulation of seismic noise by the lunar-solar tide is demonstrated. It is shown that the intensity of relaxation processes in the Earth's crust has a near-diurnal periodicity, whereas the spectrum of groundwater level fluctuations includes clearly expressed tidal waves. Based on the data on the tilts of the Earth's surface, the role of tidal deformation in the formation of the block motions in the Earth's crust is analyzed. A new approach is suggested for identifying tidal waves in the atmosphere by analyzing micropulsations of the atmospheric pressure with the use of adaptive rejection filters.

Keywords: gravitational interaction, lunar-solar tide, tidal waves, deformation, geophysical fields, seismic noise, radon emanation, groundwater, atmospheric pressure

DOI: 10.1134/S1069351317040012

INTRODUCTION

Gravitational interaction in the Earth–Moon–Sun system is one of the critical factors determining the regimes of most geodynamical processes. The self-gravity of the Earth pulls it into a sphere, whereas the attraction of the Moon and Sun changes the Earth's shape into an oblate ellipsoidal shape. This time-varying deformation of the Earth is global and captures all the Earth's shells from the inner core to the atmosphere. Due to the varying relative positions of the Earth, Moon, and Sun, the deformation caused by the attraction from the Moon and Sun migrates across the Earth's surface in the form of tidal waves. The large-scale motions of the material and deformation processes arising in the solid geospheres are accompanied by the changes in the stress state of the medium. A change in the stress-strain state of the medium causes shear displacements of the Earth's material resulting in energy dissipation. The energy of lunar-solar tides reaches ~10^{20} J per annum and is at the level of global natural energy sources such as heat inflow from the Earth's interior (~10^{21} J per annum), radioactive decay of isotopes deep in the Earth (~10^{20}–10^{21} J per annum), and the energy of tectonic deformations (~10^{19}–10^{20} J per annum) and volcanic eruptions (~10^{15}–10^{20} J per annum). This means that the lunar-solar tide is one of the most important factors determining the deformation mechanics and material transformations in the Earth's crust, as well as the regimes of the geophysical fields and intensity of interactions between the geospheres (Adushkin et al., 2006; Adushkin and Spivak, 2012). Decompaction and compaction of the Earth's material due to tidal action causes a structural rearrangement of the crust, changes the groundwater dynamics, and alters the physicomechanical properties of the rocks in the near-surface parts of the Earth (D'yakonov and Ulitin, 1982; 1988; Zhamaletdinov et al., 2000; Adushkin and Rodionov, 2005; Spivak and Khazins, 2013; Besedina et al., 2015). These effects are most pronounced in the areas controlled by the tectonic faults (Molodenskii, 1983; Marechal et al., 2002; Moussa and El Arabi, 2003; Spivak, 2010).

The change in the mechanical and electrodynamic properties of the material in the fault zones and in the crust overall, as well as the tidal variations in the groundwater dynamics, determine the pattern of geoelectrical effects which manifest themselves in the formation of persistent near-diurnal variations in the field of telluric currents and the distinct periodicities of the electric field in the ground (Korolevets and Kopylova, 2003; Kugaenko, 2005), as well as in the formation of periodicities in the discrete component of the electric field (pulsed type events) in the near-surface crustal segments (Adushkin et al., 2006).

Tidal processes also play important role in the accumulation of deformations and stresses, primarily in the zones when the medium has discontinuities (Spivak and Khazins, 2013). From this standpoint, a tidal strain wave in the medium with a hierarchical block structure significantly affects the tectonic processes in the lithosphere, including those related to the preparation of earthquakes. The existing data not only testifies to the relationship between the frequency of the occurrence of earthquakes (including weak ones) and periodicities of tidal wave (Avsyuk et al., 2002; Nikolaev, 1994; 1996; Gol'din et al., 2008; Beeler and Lockner, 2003; Nanaka et al., 2002) but also demonstrates the tidal influence on the spatial distribution of earthquake sources (Bulatova, 2005). The tidal influence on the seismicity in separate territories and on the variations of seismic noise is also supported by other studies (Knopoff, 1964; Shlien, 1972; Spivak and Kishkina, 2004; Morgunov et al., 2005; Yurkov and Gitis, 2005). It is also reported on the response of seismic noise to the lunar-solar tide (Rykunov et al., 1980; Gordeev et al., 1995; Saltykov, 1995; Spivak and Kishkina, 2004).

The tidal factor also induces a significant response in the emanation of subsoil gases. In particular, characteristic periodicities are revealed in the variations of subsoil radon volumetric activity due to the changing permeability of gas migration channels as a result of decompaction of rock material in a tidal wave (Utkin et al., 2006; Spivak et al., 2008; 2010; Choubey et al., 2011).

Tidal effects are also clearly observed in the atmospheric processes (Adushkin et al., 2016); they influence several physical processes, e.g., variation in the thermal neutron flux from the Earth's crust (Alekseenko et al., 2009), and affect global processes: inertial and resonant phenomena in the Earth's core and the processes at the core/mantle boundary (Molodenskii, 2006; Molodenskii and Molodenskaya, 2009), etc.

The influence of tidal deformation on the regimes of the electrical and magnetic fields of the Earth deserves separate mention (Saraev et al., 2002; Gokhberg et al., 2007; Sheremet'eva and Smirnov, 2007; Starjinsky, 2008; Sheremet'eva, 2011; Tereshchenko et al., 2014; Shpynev et al., 2014).

Finally, a long, persistently repeating lunar-solar tidal perturbation can be considered as a global factor causing significant displacements of the deep and near-surface masses of the Earth's material, which not only highly probably determines the spatial pattern of the large landforms, horizontal stratification of the Earth's crust, and regmatic network of the faults and fractures but also the instability (irregular pattern) of the Earth's rotation and even the observed changes in weather and climate (Sidorenkov, 2002; 2015; Revuzhenko, 2013; *Tektonicheskaya* ..., 1990; Khain, 2009; Khlystov, 2016).

All this qualifies the Earth's tide as an important factor which not only governs the rhythms and direction but, in a certain sense, acts as a trigger of the geophysical processes in the ambient environment (Adushkin and Spivak, 2012).

DATA

This study is based on the results of instrumental observations conducted in 2004–2015 in several regions of Russia: in the East European Platform, Altai Mountains, and Baikal rift zone. Together with these objects, we also used the data of the instrumental observations conducted in other regions of Russia.

Instrumental monitoring and analysis of the obtained results were carried out for the electric field in the atmospheric surface layer and in the ground, for the field of microseismic oscillations, natural radon emanation field in the form of volumetric activity of ^{222}Rn in the subsoil atmosphere, and water-table fluctuations (Adushkin et al., 2006; 2012; Adushkin and Spivak, 2006; Solov'ev and Spivak, 2007; 2009; Spivak et al., 2008; 2009b; 2009c; Spivak and Kozhukhov, 2004; Spivak and Kishkina, 2004). Also, the Earth's surface tilts were recorded. The measurements were carried out at the stationary sites (at the Center for Geophysical Monitoring (CGM) of Moscow of the Institute of Geosphere Dynamics of the Russian Academy of Sciences (IDG RAS), Mikhnevo Geophysical observatory of IDG RAS (GO MHV), Aktash Observatory of the Siberian Branch RAS, and Tory Observatory of the Institute of Solar-Terrestrial Physics of RAS) and at the operative recording sites located in the zones controlled by the tectonic faults and in the central parts of the structural blocks of the Earth's crust. Surface tilt measurements were conducted at GO MHV in the zone controlled by the deep tectonic structure—Nelidovo—Ryazan suture zone—(Spivak et al., 2009a; 2010b).

THE INFLUENCE OF A LUNAR-SOLAR TIDE ON SEISMIC NOISE

The background seismic micro-oscillations and, especially, their variations induced by external impacts are important for the geodynamical state and selectivity of the attenuation properties of the Earth's crust, as well as the Q-factor of separate resonant crustal structures. Processing the seismic data recorded in different regions demonstrates the high degree of variability of the spectral and amplitudinal characteristics of microseismic oscillations with periodicities specific to the frequency bands. The long-period micro-oscillations in the frequency band 0.1–0.5 Hz have characteristic periods of ~14, 28, 45, 60, and 365 days (an example based on the data from the GO MHV of IDG RAS is shown in Fig. 1). The high-frequency miscroseismic noise can also contain other, higher frequency periods. For instance, the 6–8 Hz frequency band has the most distinctly pronounced periodicities of 12 and 24 h with an additional period of 7 h (Fig. 1b). The presence of the fortnightly (~14 days) and near-monthly (~28 days) periodicities manifesting themselves in both the long-period and short-period parts of the spectrum is due to the modulation of seismic noise by the tidal waves M_f

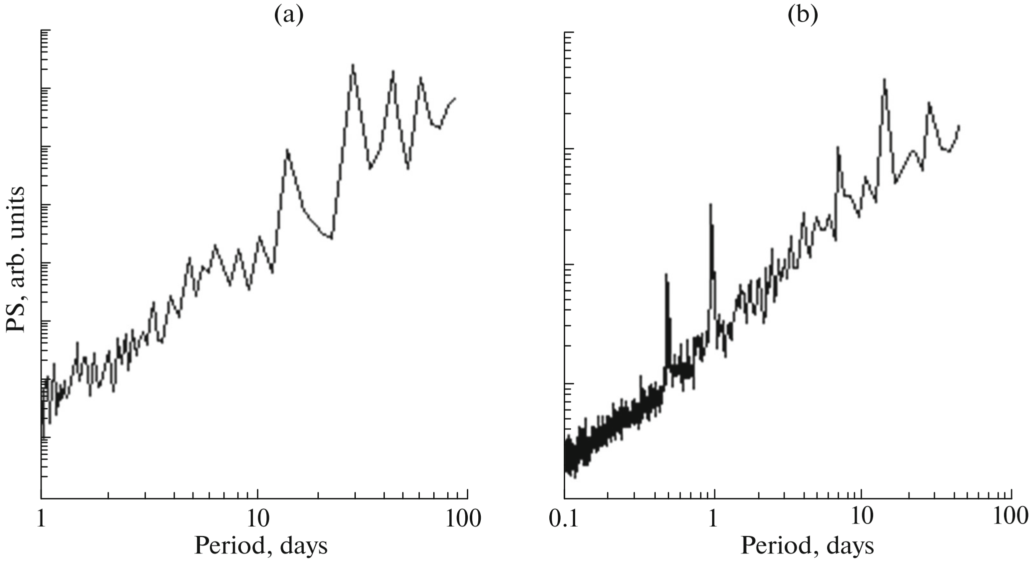

Fig. 1. The power spectrum of microseismic noise at the MHV seismic station (average over the period from 2007 to 2008); frequency band, Hz: (a), 0.1–0.5; (b), 6–8.

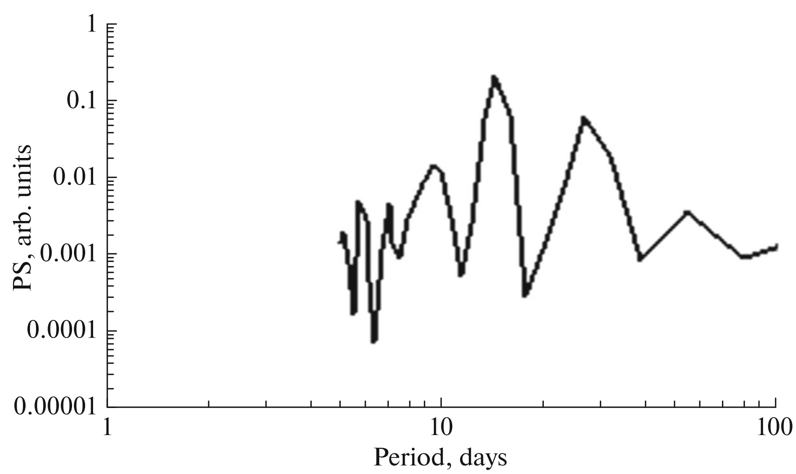

Fig. 2. The spectrum of the displacements in the microseismic noise component with a period of ~12 h.

and M_m. It is worth noting that the cited periodicities are also characteristic of the separate components of seismic noise. The example presented in Fig. 2 shows the periodogram of the variations of the spectral component of seismic noise with a period of 12 h.

The nonlinear processes taking place in the Earth's crust experiencing tidal deformation cause a characteristic response in seismic noise. As demonstrated by the instrumental observations, the correlation between the amplitude of microseismic noise in a broad range of frequencies and the magnitude of tidal force is absent (Gal'perin et al., 1987). However, such a correlation exists on separate frequency intervals ΔF, which are different for the different crustal segments (Rykunov et al., 1979; Gordeev et al., 1995; Spivak and Kishkina, 2004). Moreover, the correlation coefficient for the particular frequency intervals may reach 0.85 (see the examples of the spectral components in Fig. 3)[1]. Importantly, the maxima in the amplitude of the disturbed seismic noise and tidal force are shifted relative to each other by about 4 h (the peak in the response of the medium is reached when the rate of change of the tidal force is maximal).

We note that the mentioned modulation of the amplitude of microseismic noise is observed in the most crustal segments, including those in the high-latitude regions where tidal effect is significantly weaker (Spivak and Kishkina, 2004).

[1] Hereinafter, the magnitude of tidal force was determined, whereas the main tidal waves were identified by the ETERNA program (Wenzel, 1994).

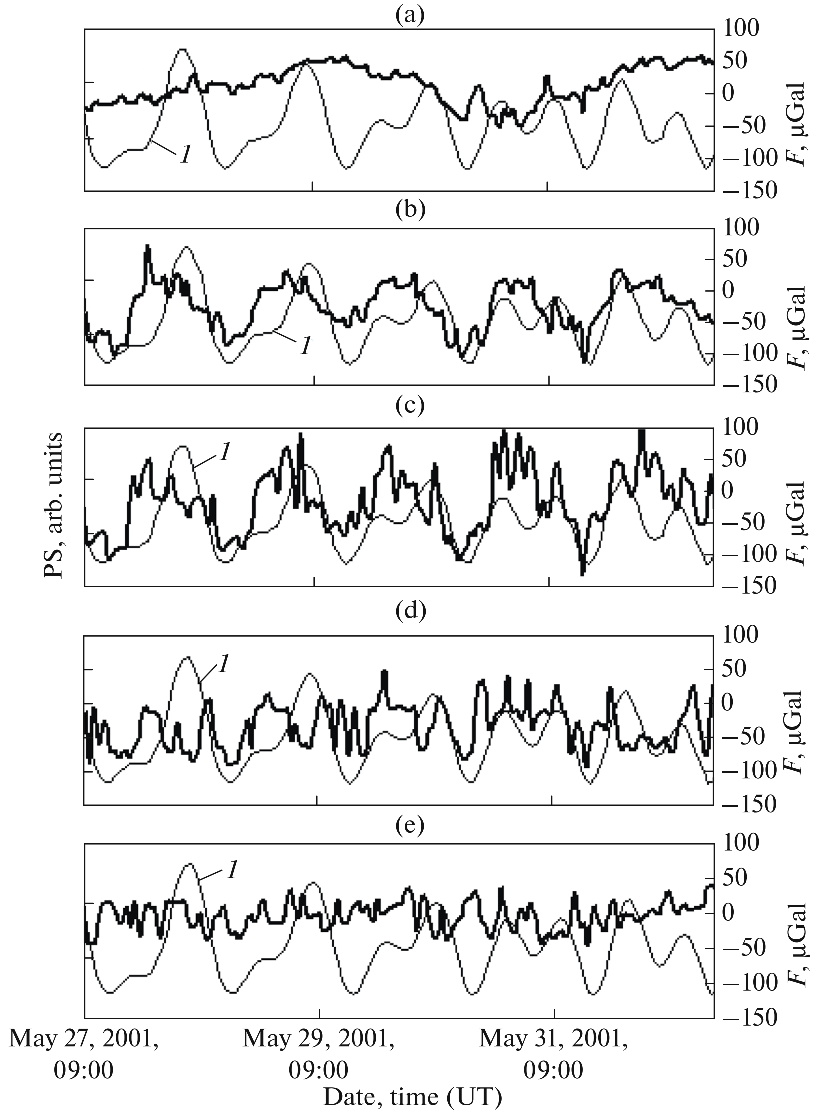

Fig. 3. The modulation of spectral components of seismic noise by tidal force; spectral component, Hz: (a), 1; (b), 2; (c), 3.8; (d), 10; (e), 15 (the thin line shows the variation of the vertical component of tidal force).

The reduced rigidity of tectonic dislocations (Spivak, 2006; 2011) and, consequently, the increased mobility of crushed rocks filling a fault zone determine the enhanced response of microseismic noise to a tidal deformation in the form of more intense amplitude variations of separate spectral components, characteristic of a particular crustal segment, compared to the central parts of the structural blocks. The example presented in Fig. 4 illustrates the microseismic noise recorded at the points located in the fault zone of the second order relative to the Nelidovo–Ryazan suture zone (Spivak, 2010a) and in the central segment of the adjacent block. For comparison, the variations of tidal force F are also shown. It can be seen that the time variations of the root mean square (RMS) amplitude of microseismic noise A (in our case, in the frequency band 7–10 Hz) is noticeably higher in the fault zone. At the same time, we note the highly significant correlation between A and F (Spearman's rank correlation coefficient is $K = 0.71$ with the significance level $\rho \leq 0.05$) when a certain advance of the microseismic noise response to the tide is taken into account (the maximum in the amplitude of the variations of microseismic noise coincides with the maximum of the derivative F').

TIDAL EFFECT ON RADON EMANATION

The role of tidal deformation in the emanation processes can be most illustratively considered by the example of a radon—a radioactive gas which is readily detectable in practice. The measurements of natural radon ^{222}Ra volumetric activity in the subsoil atmosphere (Spivak et al., 2009b) testify to the presence of

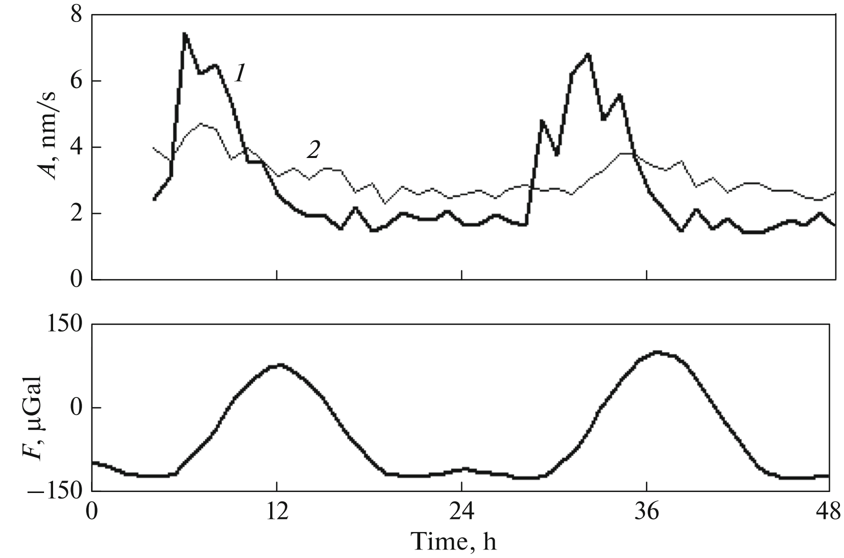

Fig. 4. Variations in the amplitude of microseismic noise A in the frequency band 7–10 Hz at the observation points located (*1*) on the tectonic fault of order II and (*2*) outside the zone controlled by this fault; the bottom panel shows the vertical component of tidal force F.

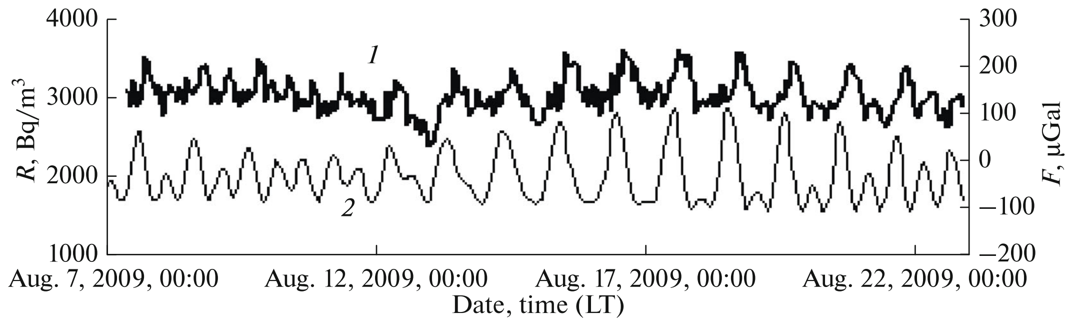

Fig. 5. (*1*) Variations in subsoil radon volumetric activity R at the point located in the Tunka rift zone; (*2*), vertical component of tidal force F.

significant time variations in the intensity of the emanations. The data of the instrumental observations demonstrate the presence of periodicities in the time variations of the subsoil radon volumetric activity R with periods of 12 and 24 h and 14 days (Figs. 5, 6). Although pronounced to a different degree, these periodicities in radon emanation intensity are observed ubiquitously. They are most distinctly expressed in the zones controlled by large tectonic structures. The example presented in Fig. 7 shows the time variations in the subsoil radon volumetric activity recorded in the area controlled by the Nelidovo–Ryazan suture zone and in the central segment of the structural block adjacent to this zone. The presence of peaks with periods of 0.5 and 1 day, which are clearly distinguished against the background of the other spectral components, due to the inertia of the emanation process reflect the total effect of the groups of M_2, S_2, N_2, and K_2 tidal waves having periods of ~12 h and the P_1, K_1, and O_1 tidal waves with periods of ~24 h.

The coincidence of the characteristic periodicities in the time variations of R and F suggests the probable existence of a significant correlation between the vertical component of the tidal force, which determines the degree of decompaction of the Earth's material in the tide bulge, and subsoil radon volumetric activity. The correlation between the variations in R and tidal force F is visually observed in the graphs in Figs. 5 and 7. A more thorough analysis shows that in the subsoil radon volumetric activity spectra there are distinct peaks corresponding to the tidal waves S_2 and M_2. This is illustrated by the example in Fig. 8a, which shows the cross correlation spectrum of the variations in the subsoil radon volumetric activity and vertical tidal force component S_{RF} at the measurement point located in the Tunka rift zone.

The calculations of the time-lagged correlations between the variations of R and F show that the maximal correlation coefficient in many cases approaches 0.7 and the peak is achieved with the radon emanation

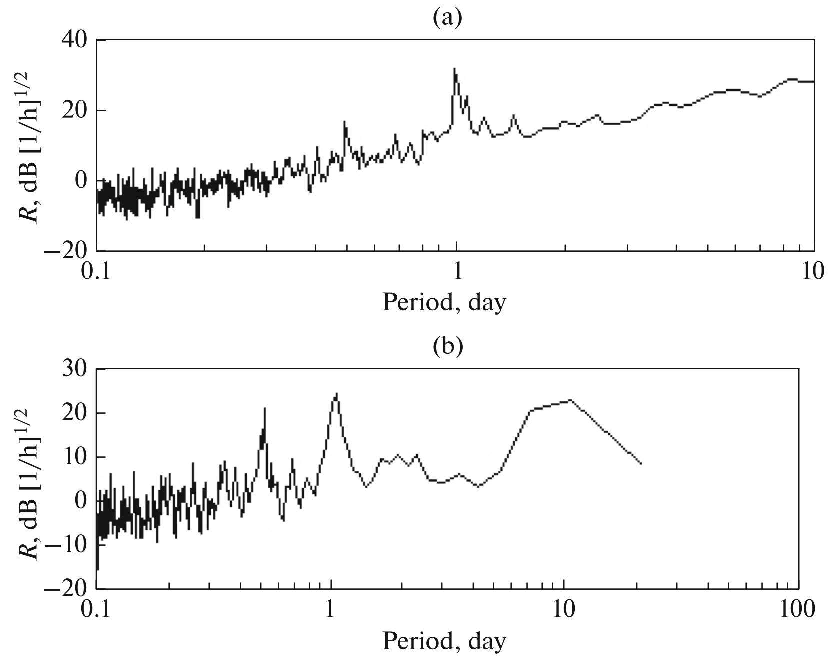

Fig. 6. The power spectrum of subsoil radon volumetric activity in the (a) Nelidovo-Ryazan' suture zone and (b) Tunka rift zone.

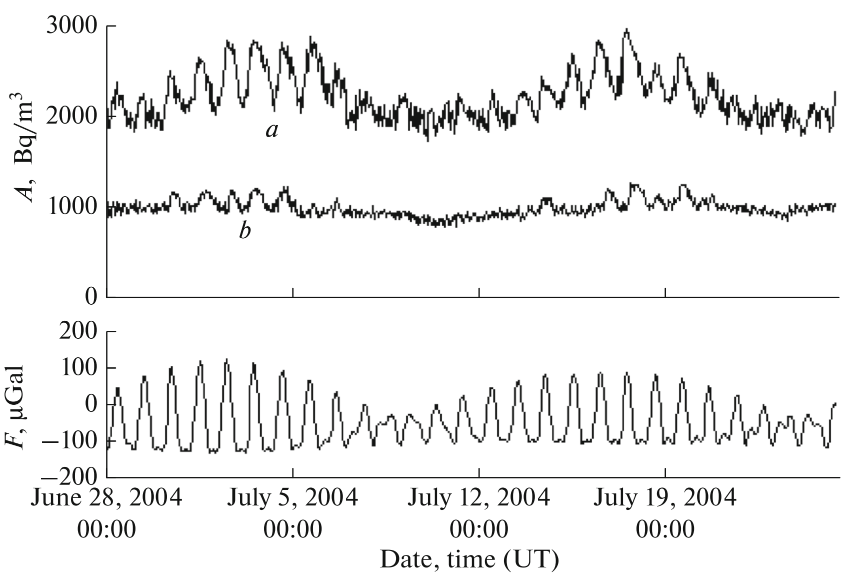

Fig. 7. Variations in the subsoil radon volumetric activity *R* under the long stable weather conditions at the point located (*a*) in the area controlled by the Nelidovo-Ryazan suture zone and (*b*) in the structural block of the Earth's crust; *F* is the vertical component of tidal force.

field delayed by ~3–4 h relative to the tidal deformation with the different segments of the Earth's crust (Fig. 8b).

Hence, we may state a significant influence of the tidal deformation of the medium on the intensity of radon emanations.

THE INFLUENCE OF A TIDE ON THE GROUNDWATER-LEVEL FLUCTUATIONS

The existing data testify to the high sensitivity of hydrogeological conditions to the external perturbations, including tidal effects (Marechal et al., 2002;

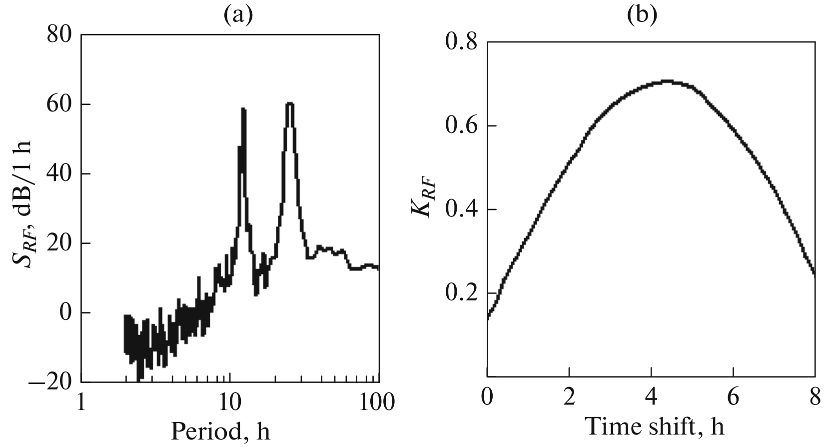

Fig. 8. (a) The cross spectrum of the subsoil radon volumetric activity and tidal force (the Tunka rift zone) and (b) correlation coefficient K_{RF}.

Adushkin et al., 2012). This is not surprising because the deformation of the Earth's material in a tidal wave leads to significant changes in the micro- and macrostructure of the medium. Indeed, the growth in a tidal force causes deformations associated with the expansion of the medium and, hence, leads to the increase in porosity and permeability. On the contrary, a decrease in a tidal force causes the medium to compress; i.e., it reduces the medium's permeability. These effects are most distinct in the zones of the reduced strength of the medium—in faults and large fractures.

The alternating deformation of the medium naturally induces periodical variations in the groundwater fluctuations.

The example in Fig. 9 shows the periodograms of groundwater fluctuations in the well, S_W, and variations in the tidal force, S_F, during a 70-day interval from July 19 to September 30, 2008 according to the results of instrumental observations at the GO MHV of IDG RAS.

The S_W spectrum has clearly expressed spectral peaks reflecting the presence of quasi-harmonic periodicities in the groundwater level fluctuations. As seen from Fig. 9, the semidiurnal and near-diurnal periodicities with periods of ~12 and 24 h (groups of spectral peaks *1*, *2* and *3*, *4* in Fig. 9, respectively) and the cycle with $T \sim$ 12–14 days (peak *8*) closely agree with the periods of the corresponding tidal waves. The good coincidence of the periodicities and the high coefficient of correlation $K \sim 0.73$–0.82 between the variations in S_W and S_F testify to the significant role played by tidal deformations in the variations of local hydrogeological conditions and, hence, in the work of tidal forces acting as a tectonic pump (Shilo and Vashilov, 1989).

Besides, just as in the case of the variations of the block's tilt, the peaks with the close periods in groups *1*, *2* and *3*, *4* in the groundwater level fluctuations spectrum are clearly separated reflecting tidal waves S_2, M_2 and K_1, O_1, respectively (Fig. 10). This demonstrates the high sensitivity of the dynamics of groundwater level fluctuations to variations in the tidal force.

The other periodicities with periods $T \sim$ 3, 4, and 5 days (spectral peaks *5*–*7* in Fig. 9) are caused by the influence of baric variations in the atmosphere. The correspondence of the different periodicities in the groundwater level fluctuations to the tidal deformations is illustrated in Fig. 11, which shows a cross spectrum of groundwater level fluctuations and tidal force K_{WF}.

THE INFLUENCE OF A TIDE ON THE RELAXATION PROCESSES AND PULSED ELECTRIC FIELD COMPONENT IN THE EARTH'S CRUST

The deformation of the Earth's material in the form of alternating phases of compression and expansion, which results from the gravitational interaction in the Earth–Moon–Sun system, significantly affects the intensity of the relaxation processes—the release of mechanical stresses accumulated in the medium. The decompaction of a medium in a tide bulge facilitates the mobility of the confined crustal blocks, which produces additional favorable conditions for their relaxation. In the simplest case, the intensity of the relaxation process can be described by the number of acts of relaxation each of which is accompanied by a characteristic microseismic pulsed signal (Spivak and Kishkina, 2004). An example is presented in Fig. 12 which illustrates the simultaneously recorded variations in the number of the relaxation-related microseismic pulses N_A and the vertical component of tidal force F. It can be seen that there is a significant correlation between the intensity of the relaxation processes in the medium and the variations in F (the linear Pearson correlation coefficient is $K = 0.86$).

Since a considerable part of the electric pulses recorded in the near-surface crustal segments are

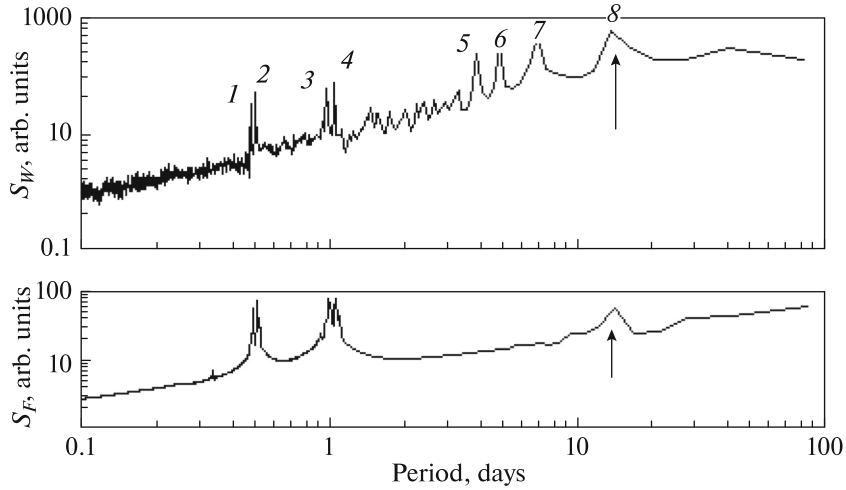

Fig. 9. The periodogram of the groundwater level fluctuations in the open well at GO MHV (S_W) and tidal force (S_F); *1–8*, the spectral peaks; the vertical arrows show the spectral peaks corresponding to the biweekly periodicities of the tidal force.

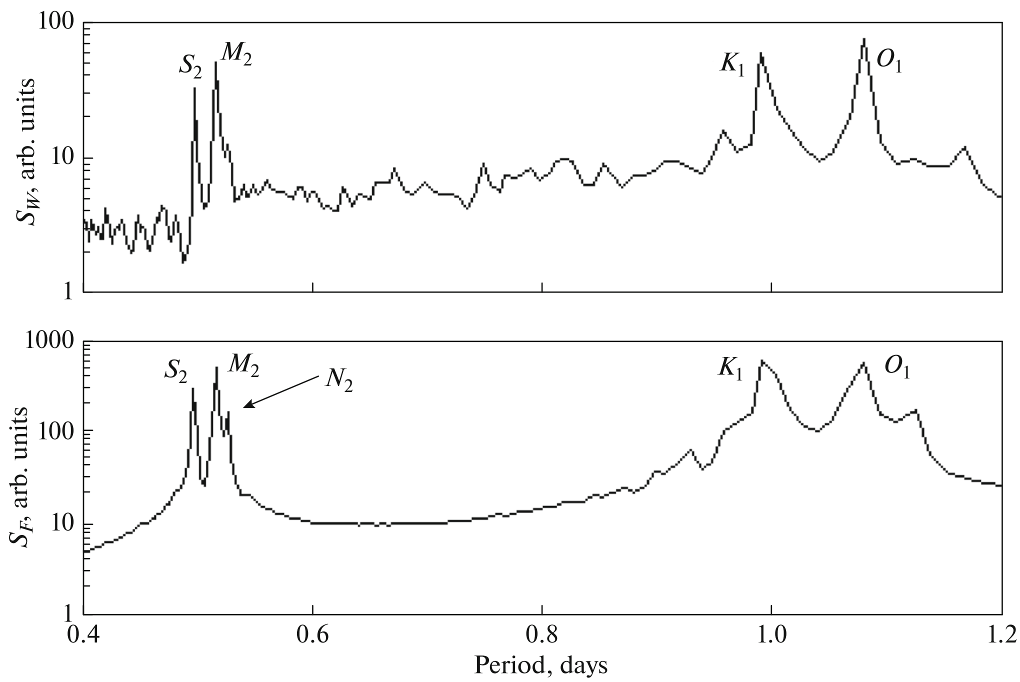

Fig. 10. Near-diurnal periodicities in the fluctuations of the groundwater level S_W and tidal force S_F; S_2, M_2, N_2, K_1, and O_1 are the periods of the corresponding tidal waves.

related to the mechanical movements in the hierarchical block medium[2] (Soloviev and Spivak, 2009), it is interesting to explore the discrete characteristics of the electric field in the ground. The joint analysis of the microseismic and electrical measurements in the case when an electric signal is accompanied by seismic pulses suggests (Soloviev and Spivak, 2009) that the electric and microseismic signals are very likely to be generated in the same source. As one of the most probable generation mechanisms, we may consider differential displacements of crustal blocks when their active sides are a source of the electric signals. According to the calculations, in this case the parameters of the electric pulses closely agree with the results of the instrumental observations (Loseva et al., 2010; 2012).

[2] This does not contradict the notions according to which pulsed electric signals in the ground are caused either by a change in the established current systems or by a step-like charge separation. In a solid medium with a heterogeneous structure both of them can be accounted for by the mechanical processes associated with the fracturing and differential displacements of structural blocks (Loseva et al., 2010; 2012).

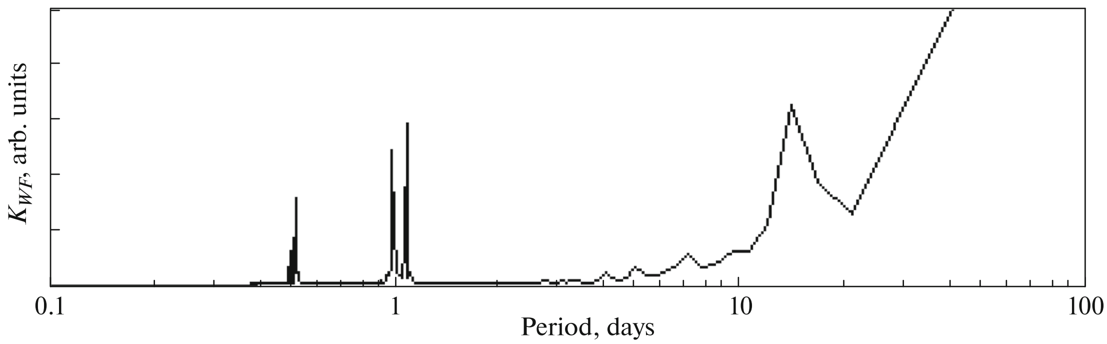

Fig. 11. The cross spectrum of the water level fluctuations in open well and the tidal force (K_{WF}).

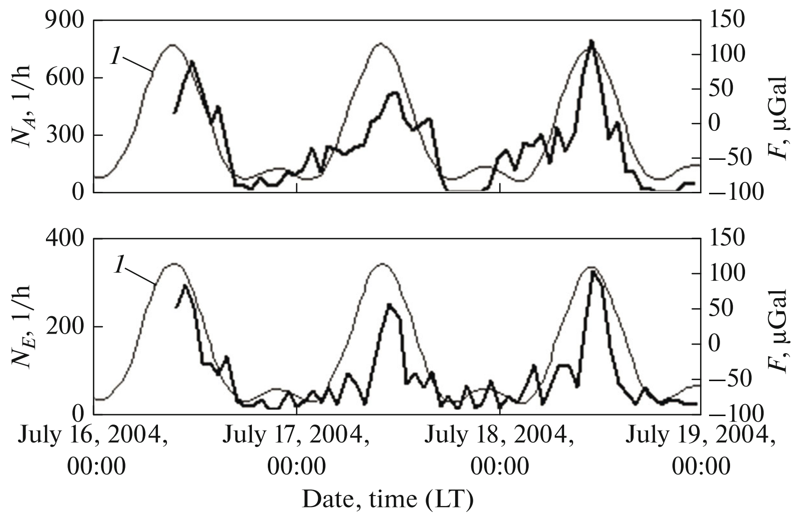

Fig. 12. The number of the acts of relaxation N_A and electric pulses in the ground N_E in the zone controlled by the Kurai fault (Mountainous Altai); F is the vertical component of tidal force (the thin lines *1*).

The analysis of the synchronous observations of the electric pulses in the ground and relaxation-related seismic pulses shows that the statistics of the discrete component of the electric field in the ground is correlated with the variations in the tidal force. This is illustrated by Fig. 12 showing the time variation of the number of electric pulses N_E recorded on one crustal segment. The Pearson linear correlation coefficient $K = 0.78$ supports a significant correlation between the electric pulse rate in the medium and variations in F.

MOTION OF CRUSTAL BLOCKS IN A TIDAL WAVE

The mechanical properties of the Earth's material, primarily, in the fault zones, play the predominant role in the formation of the dynamics of the geophysical fields (Kuzmin, 2004; Spivak, 2010c). Considering this fact, the changes in these properties should be treated as one of the key factors determining the variation in the regimes of geodynamical processes in the Earth's crust. Here, it should be taken into account that the transformation of the material composing the fault zones is not entirely determined by the sizes and material composition of the latter but also by the intensity of deformation of these zones through differential displacements of crustal blocks adjacent to the fault. Importantly, besides the translational and rotational displacements which are observed in the crust, there are also short-term motions which are close to the precession. In particular, these motions were recorded during the highly precise measurements of the Earth's surface tilts in two mutually orthogonal directions aimed at determining the tilts of the crustal structural block with a linear size of ~20 km (Spivak et al., 2009a)[3].

As an example, Fig. 13 shows the variations in the Earth's surface tilts relative to the trend component, which are close to the variations of the tidal force F. Together with the cited periodicities, the graph also shows a clear fortnightly periodicity which coincides in character with the biweekly cycle of the variations in

[3] The integrity and homogeneity of the block was substantiated by the results of the geological studies.

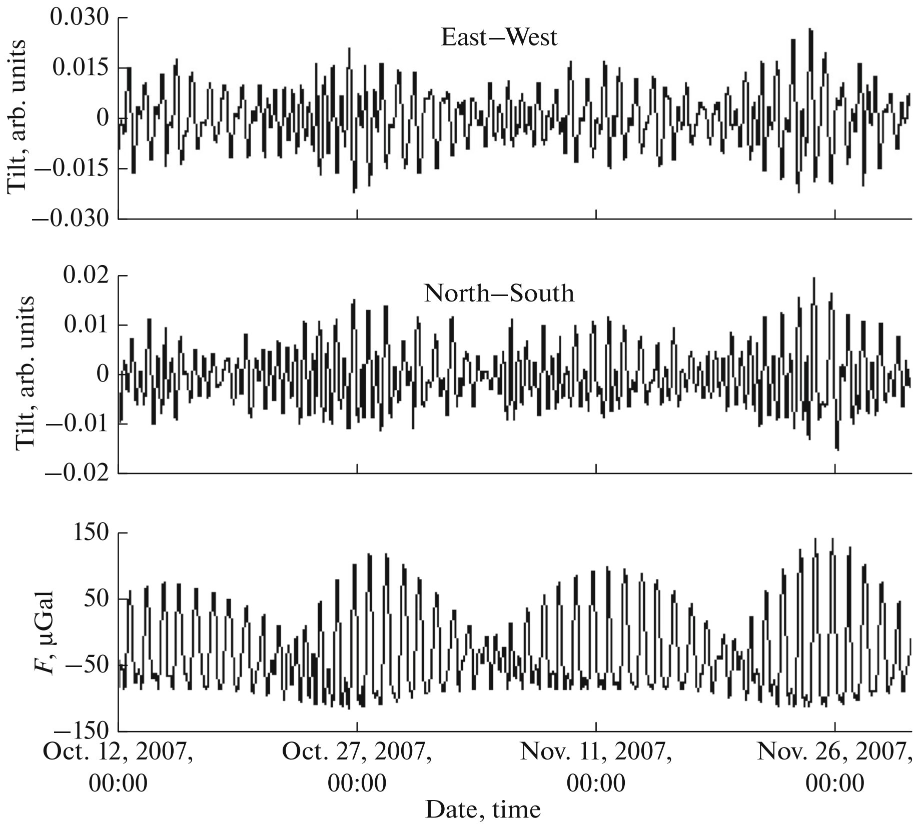

Fig. 13. The example of the detrended near-diurnal variations in tidal tilts of a crustal block; F is the vertical component of tidal force.

the tidal force. We note that the tilt variation spectrum (Fig. 14) contains well-pronounced peaks associated with the response of the block motion to the semidiurnal and diurnal tidal waves S_2 (with a period of 12 h), M_2 (12.42 h), K_1 (23.93 h), and O_1 (25.81 h) which are characterized by the most significant displacements. The analysis of the data demonstrates a significant correlation between the variations in the tilt angles of the block and the changes in the tidal force F (Spearman's rank correlation coefficient throughout the observation period is 0.7–0.8 with a significance level of at worst 0.995) (Adushkin et al., 2012).

TIDAL WAVES IN THE EARTH'S ATMOSPHERE

An atmospheric tide plays quite a significant role in the formation of the mean characteristics of air mass motion on both the global and local scale (Adushkin et al., 2016b; Golitsyn, 2004; Sidorenkov, 2002; 2015; Chapman and Lindzen, 1970; Zurbenko and Portzeva, 2009). In contrast to the tidal effect in the Earth's crust and lithosphere, an atmospheric tide occurs as a result of three factors: the gravitational impact from the Moon and the Sun (gravitational component of the atmospheric tide), the Earth's rotation, and the heating of the atmosphere on the sunward side of the Earth, with the intensity determined by the absorption of solar energy and with the diurnal periodicity coinciding with the period of the gravitational tidal wave S_1 (thermal component of the atmospheric tide).

The importance of the study of an atmospheric tide is mainly dictated by the need to refine the known and reveal new morphological features in the global and local distributions of the tidal variations in the atmospheric pressure, as well as to establish the vector characteristics of the atmosphere (wind-driven motions of air masses). This is vital, for example, in the operation of aircraft. The data on tidal perturbations in the atmosphere are necessary for elaborating the model of the Earth's interior, including the interactions at the core/mantle boundary, because the Earth's structure determines the frequency and amplitude of its near-diurnal nutation. Due to this, the analysis of the discrepancies between the observed and predicted amplitudes of nutation harmonics, which is based on the data about the tidal effects in the atmosphere (Sidorenkov, 2002), provides a good means for elaborating the Earth's models.

An atmospheric tide also plays a significant role in the formation of temperature anomalies on the Earth. The presence of lunar cycles with the periods of

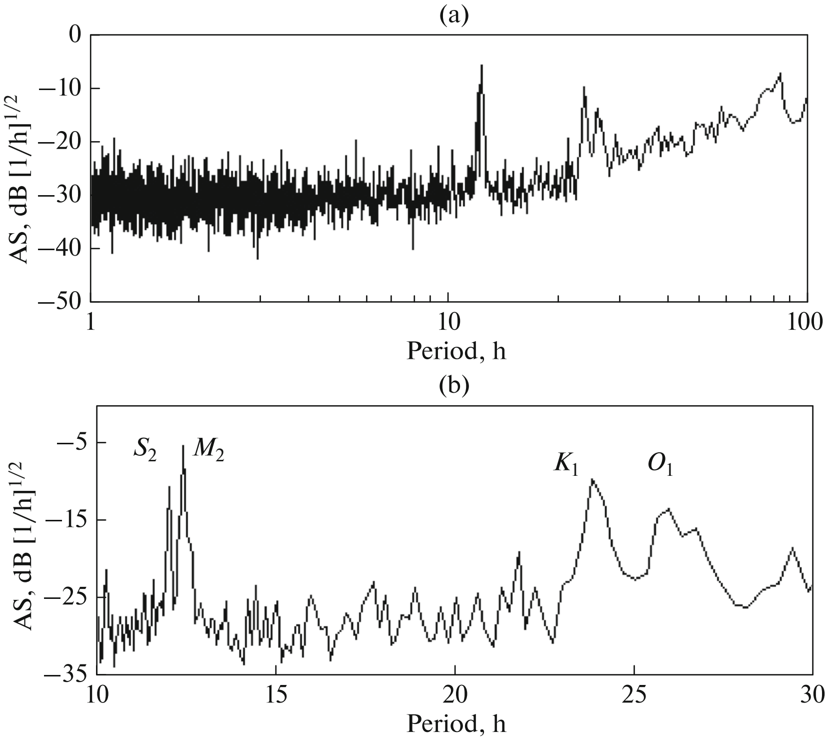

Fig. 14. The amplitude spectrum (AS) of the variations in the tilt angle of the block in the east–west direction (average over the period from September 7, 2007 to January 20, 2008).

355 days (tidal year), 206 days (evection half-period), and 27 days (sidereal month) in the air temperature spectra qualifies the tidal factor as one of the key sources of the cyclic temperature anomalies on Earth (Sidorenkov, 2015). The information about tidal variations in the atmospheric parameters and about the superposition of tidal waves is not only applicable for forecasting the temperature anomalies like those of 1972 and 2002 but it also enables the estimation of climatic changes on Earth (Sidorenkov, 2015).

The study of atmospheric tides based on the analysis of time variations in the atmospheric pressure is fraught with well known difficulties. The rather weak tidal effects are poorly distinguishable against the intense air pressure variations induced by the baric perturbations of the atmosphere by cyclones and anticyclones. Even when the analyzed air pressure time series are sufficiently long, only a certain part of the tidal waves can be revealed (Zurbenko and Portzeva, 2009). This is illustrated by the example in Fig. 15 showing the amplitude spectra of air pressure variations at GO MHV and CGM calculated over the observation period from 2008 to 2015. The data in Fig. 15 clearly demonstrate the intervals characterized by the different turbulence scales. There is one distinct maximum observed at a frequency of ~0.0835 1/h which can be interpreted as the tidal wave K_2 (with a period of 0.499 day).

In the vicinity of the diurnal period, the spectrum contains the components of tidal waves K_1 and P_1 with periods of 1.0027 and 0.9973 days, respectively, which are however not fully expressed. The spectral interval in the vicinity of periods of 0.5 days and 1 day in the form of the corresponding periodograms is shown in Fig. 16. The data in Figs. 15 and 16 indicate that even when we consider sufficiently long time series of air pressure measurements, the analysis cannot reveal and, therefore, isolate the entire spectrum of the tidal waves, which is likely to be due to the strong influence of the cyclonic processes taking place in the middle latitudes. For identifying tidal waves in the atmosphere, in (Adushkin et al., 2016) it was suggested to analyze micropulsations of the atmospheric pressure instead of its absolute value. Indeed, this approach with adaptive rejection filters (Widrow et al., 1975; Widrow and Stearns, 1986) allows identifying practically all the known tidal waves. This is illustrated by the example in Fig. 17 showing the air pressure micropulsation spectra in the vicinity of the semidiurnal and near-diurnal periods for the conditions of Moscow.

The results of processing and analyzing the instrumental observations of the air pressure micropulsations indicate that, considering the uncertainty of the spectral estimates, the periods of the identified quasi harmonic components correspond to the periods of the main tidal waves. We note that in this case, in contrast to the Earth's tides, the spectral amplitudes of

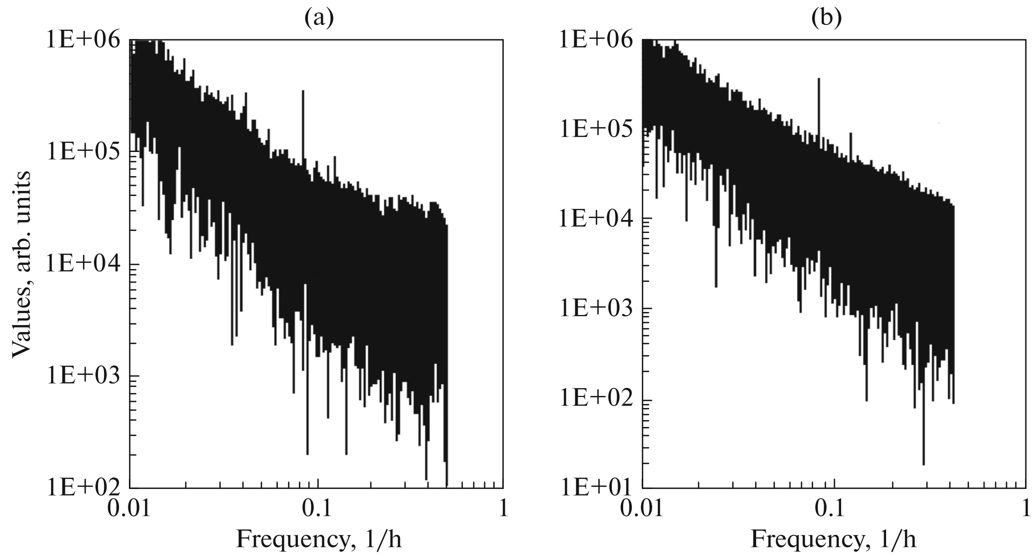

Fig. 15. The spectrum of the air pressure variations (a) at GO MHV and (b) in Moscow.

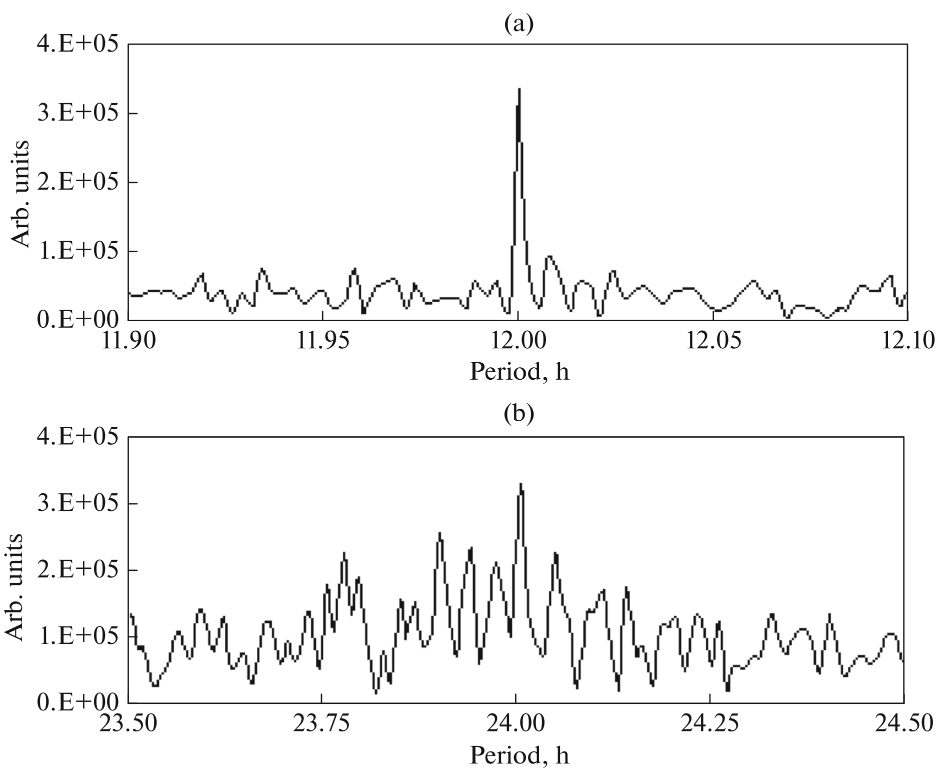

Fig. 16. (a) Semidiurnal and (b) near-diurnal intervals of the air pressure variations spectrum at GO MHV.

solar tides are higher than the amplitudes of lunar tides. This is a well known fact reflecting the additional impact from the terminator—the thermal solar tide (Chapman and Lindzen, 1970).

The amplitudes of tidal waves significantly vary with time in accordance with the changes in the mutual position of the Earth, Moon, and Sun. An example of the variations in the relative spectral amplitudes of several tidal waves calculated from the data of this work is presented in Fig. 18. The graphs show the clearly expressed periodicities in the variations of the considered quantities: for instance, the amplitude of tidal wave K_2 varies with a period of ~4.8 months. The time variation in the amplitude of solar elliptical

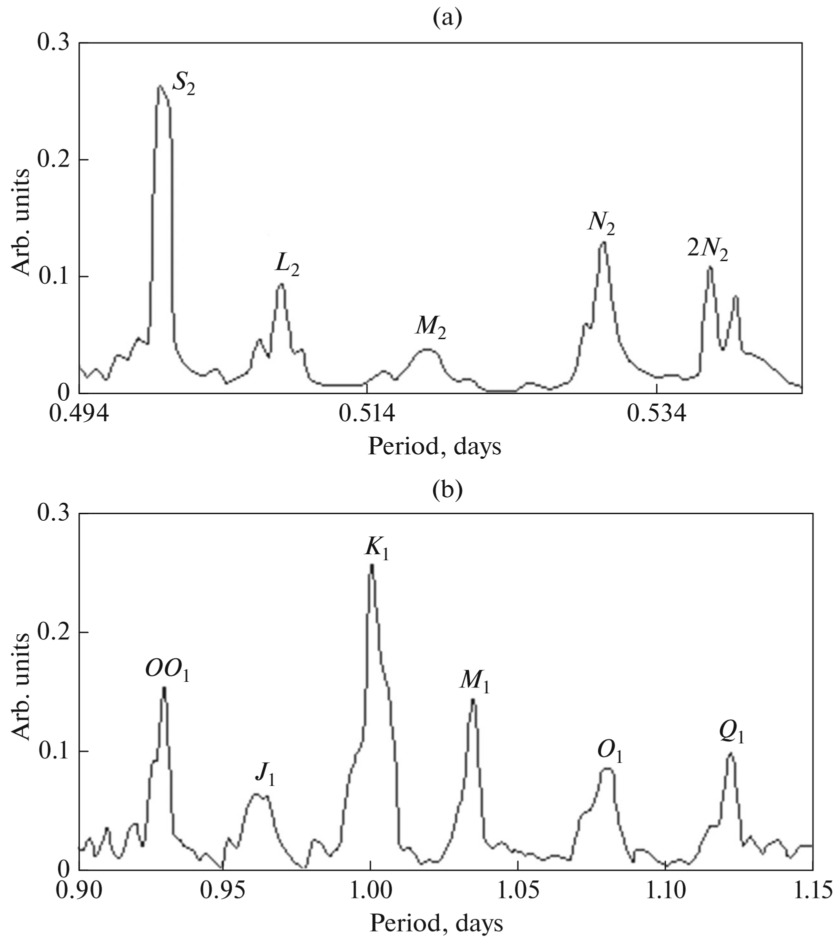

Fig. 17. (a) Semidiurnal and (b) near-diurnal intervals of the air pressure variations spectrum in Moscow.

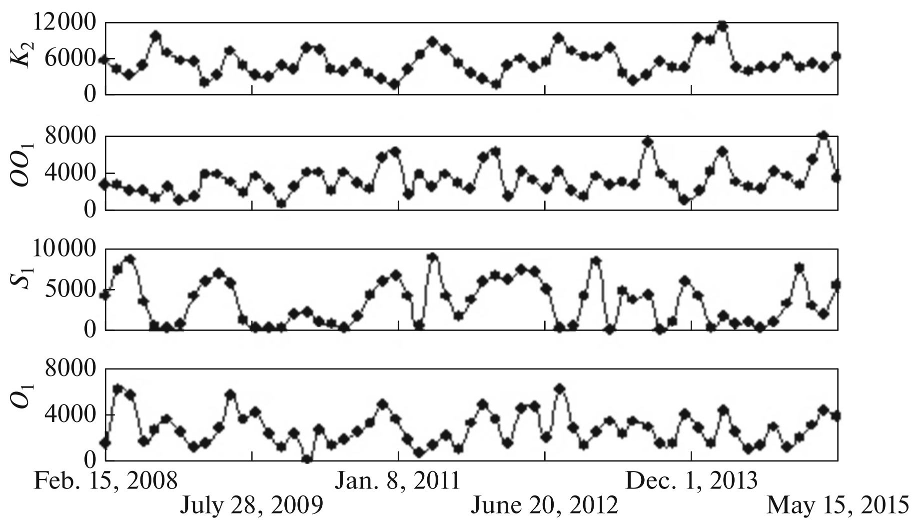

Fig. 18. Amplitude variations of the main tidal waves during the analyzed time interval at GO MHV.

wave S_1, which alternates between reaching the maximal values (commensurate with and even exceeding the amplitudes of the stably recorded waves such as K_2, L_2, and M_2) and becoming negligible is particularly interesting. Since the tidal wave S_1 reflects the thermal component of the atmospheric tide, the growth and

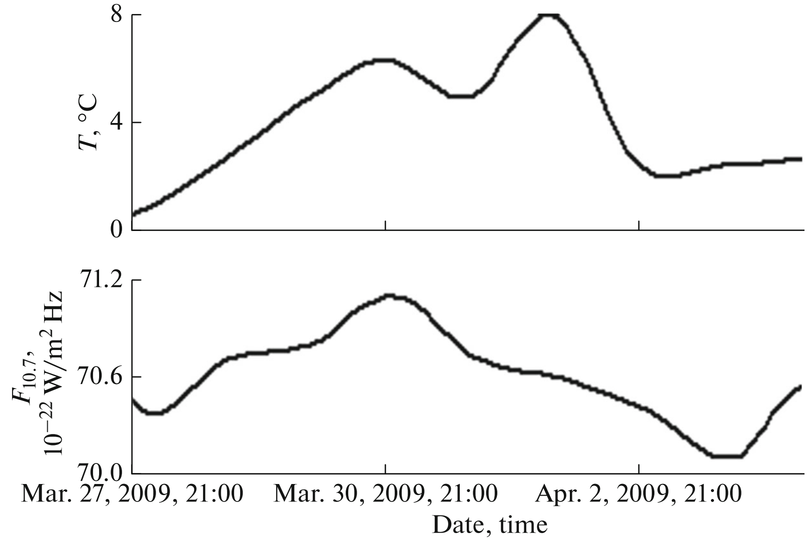

Fig. 19. The variations in air temperature and solar activity index during the period of the increased amplitudes of tidal wave S_1.

decay of its amplitude should be determined by the degree of atmospheric heating, i.e., by the intensity of the temperature variations. According to the observations, the solar tidal wave S_1 reaches its maximal amplitudes during the intervals of the increased relative air temperature T. This is clearly seen in Fig. 19, showing a fragment of temperature variations for one of the time intervals where (i) there is a clearly pronounced tidal wave S_1 and (ii) its amplitude has an increased value (Fig. 18).

Since the air temperature is determined by solar heating, it would be interesting to compare the amplitude variations of tidal wave S_1 with the intensity of solar radiation. Let us characterize the level of solar radiation by the solar activity index $F10.7$, which describes the intensity (flux density) of the solar radio flux at a frequency of 2800 Hz (wavelength 10.7 cm). The analysis of the data shows that the growth phases of solar activity (in terms of $F10.7$) coincide with the intervals of increasing air temperature (Fig. 19) and, correspondingly, increasing amplitudes of tidal wave S_1. This is the case despite the fact that, according to the estimates (*Atmosfera* ..., 1991), the observed variations in $F10.7$ during the considered time period change the exoatmospheric solar flux by at most 0.3%. This observation requires additional research, with the establishment of the probable physical mechanisms of the influence of space weather factors on the near-Earth atmosphere.

CONCLUSIONS

The results of the instrumental observations testify to the synchronism and significant correlation between the time variations of the considered geophysical fields and the changes in the vertical component of the tidal force. This allows a lunar-solar tide to be considered as one of the most important factors which not only determine the behavior and rhythms of the mechanical and physical processes accompanying the deformation of the Earth's material and its transformation as a result of periodic decompaction but also play an important role in the formation of the regimes of the geophysical fields. In this sense, the Earth's tide is a fundamental mechanism created by Nature, which largely determines the planetary evolution of the Earth.

The presented data illustrate the difficulty of identifying the near-diurnal and semidiurnal groups of tidal waves in the atmosphere by analyzing the variations in the air pressure. The suggested approach, which is based on analyzing micropulsations in the air pressure using the adaptive rejection filters, is capable of identifying practically all the known tidal waves (in this case, it is necessary to use the data on the frequency characteristics of tidal waves recorded in the Earth's crust for forming the set of frequencies to be analyzed and for estimating the synthesized spectrum).

REFERENCES

Adushkin, V.V. and Rodionov, V.N., On the nature of mechanical motion in the Earth's interior, *Izv. Akad. Nauk, Fiz. Zemli*, 2005, no. 2, pp. 88–91.

Adushkin, V.V., Spivak, A.A., Kishkina, S.B., Loktev, D.N., and Solov'ev, S.P., Dynamic processes in the system of interacting geospheres at the Earth's crust–atmosphere boundary, *Izv., Phys. Solid Earth*, 2006, vol. 42, no. 7, pp. 567–584.

Adushkin, V.V. and Spivak, A.A., Near-surface geophysics: complex investigations of the lithosphere–atmosphere interactions, *Izv., Phys. Solid Earth*, 2012, vol. 48, no. 3, pp. 181–198.

Adushkin, V.V., Spivak, A.A., and Kharlamov, V.A., Effects of lunar–solar tides in the variations of geophysical fields at the boundary between the Earth's crust and the atmosphere, *Izv., Phys. Solid Earth*, 2012, no. 2, pp. 104–116.

Adushkin, V.V., Spivak, A.A., and Kharlamov, V.A., Results of instrumental observations of tidal wave propagation in the atmosphere, *Dokl., Earth Sci*., 2016, vol. 469, no. 1, pp. 758–761.

Alekseenko, V.V., Gavrilyuk, Yu.M., Gromushkin, D.M., et al., Correlation of variations in the thermal neutron flux from the Earth's crust with the Moon's phases and with seismic activity, *Izv., Phys. Solid Earth*, 2009, vol. 45, no. 8, pp. 709–718.

Atmosfera. Spravochnik (The Atmosphere: A Handbook), Leningrad: Gidrometeoizdat, 1991.

Avsyuk, Yu.N., Khudzinskii, L.L., and Suvorova, I.I., Relationship between the Earth's seismicity and tidal impacts from the Moon and the Sun, *Vychisl. Seismol*., 2002, no. 33, pp. 311–336.

Beeler, N.M. and Lockner, D.A., Why earthquakes correlate weakly with the solid Earth tides: effects of periodic stress on the rate and probability of earthquake occurrence, *J. Geophys. Res.*, 2003, vol. 108, no. B8, pp. 2391–2405.

Besedina, A.N., Vinogradov, E.A., Gorbunova, E.M., et al., The response of fluid-saturated reservoirs to lunisolar tides: Part 1. Background parameters of tidal components in ground displacements and groundwater level, *Izv., Phys. Solid Earth*, 2015, vol. 51, no. 1, pp. 70–79.

Bulatova, N.P., Latitudinal distribution of the Earth's seismicity depending on the position of the Sun and the Moon, *Vulkanol. Seismol.*, 2005, no. 2, pp. 57–78.

Cartwright, D.E. and Tayler, R.I., New computations of the tide-generating potential, *Geophys. J. R. Astron. Soc.*, 1971, vol. 23, no. 1, pp. 45–47.

Chapman, S. and Lindzen, R.S., *Atmospheric Tides*, Dordrecht: D. Reidel, 1970.

Choubey, V.M., Arora, B.R., Barbosa, S.M., Kumar, N., and Kamra, L., Seasonal and daily variation of radon at 10 m depth in borehole, Garhwal Lesser Himalaya, India, *Appl. Radiat. Isot.*, 2011, vol. 69, pp. 1070–1078.

D'yakonov, B.P. and Ulitin, R.V., Earth tides and variations in the physical characteristics of rocks, *Dokl. Akad. Nauk SSSR*, 1982, vol. 264, no. 2, pp. 322–325.

Gal'perin, E.I., Vinnik, L.P., and Petersen, N.V., On the modulation of high-frequency seismic noise by tidal deformations of the lithosphere, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1987, no. 12, pp. 102–109.

Gokhberg, M.B., Kolosnitsyn, N.I., and Nikolaev, A.I., Tidal deformations and the electrokinetic effect in a two-layer fluid-saturated porous medium, *Izv., Phys. Solid Earth*, 2007, no. 8, pp. 702–706.

Goldin, S.V., Timofeev, V.Yu., van Ruymbeke, M., Ardyukov, D.G., Lavrentiev, M.E., and Sedusov, R.G., Tidal modulation of low seismicity in Southern Siberia, *Fiz. Mezomekh*, 2008, vol. 11, no. 4, pp. 81–93.

Gordeev, E.I., Saltykov, V.A., Sinitsyn, V.I., and Chebrov, V.N., On the correlation between the high-frequency seismic noise and lunisolar tides, *Dokl. Akad Nauk*, 1995, vol. 340, no. 3, pp. 386–388.

Khain, V.E., On the main trends in present-day Earth sciences, *Herald Russ. Acad. Sci.*, 2009, vol. 79, no. 1, pp. 57–63.

Khlystov, A.I., Zonal tide as a probable cause of emergence of "critical latitudes" on the Earth, in *Tektonofizika i aktual'nye voprosy nauk o Zemle*, T. 2 (Tectonophysics and Topical Problems in the Earth Science, vol. 2), Moscow: IFZ, 2016, pp. 623–629.

Knopoff, L., Earth tides as triggering mechanism of earthquakes, *Bull. Seismol. Soc. Am.*, 1964, vol. 54, pp. 1865–1870.

Kocharyan, G.G., Gorbunova, E.M., Kopylova, G.N., Pavlov, D.V., and Svintsov, I.S., Preliminary results of high-precision observations of the groundwater dynamics in the territory of the Mikhnevo Geophysical Observatory, in *Lokal'nye i global'nye proyavleniya vozdeistvii na geosfery* (Local and Global Manifestations of the Impacts on the Geosphere), Moscow: GEOS, 2008, pp. 52–62.

Krolevets, A.N. and Kopylova, G.N., Tidal components in the electrotelluric field, *Izv., Phys. Solid Earth*, 2003, vol. 39, no. 5, pp. 418–427.

Kugaenko, Yu.A., Specific properties of the geoelectric response of the medium to the tidal effect, *Izv., Phys. Solid Earth*, 2005, vol. 41, no. 7, pp. 571–579.

Kuz'min, Yu.O., Recent geodynamics of fault zones, *Izv., Phys. Solid Earth*, 2004, vol. 40, no. 10, pp. 868–882.

Losseva, T.V., Kuz'micheva, M.Yu., and Spivak, A.A., Electric and magnetic signals due to constrained movement of blocks of the Earth's crust, *Dokl. Earth Sci.*, 2010, vol. 432, no. 2, pp. 808–811.

Loseva, T.V., Spivak, A.A., and Kuz'micheva, M.Yu., A Dipole model of generating electric pulses in relaxation processes in the Earth's crust, *Dokl. Earth Sci.*, 2012, vol. 442, no. 1, pp. 159–162.

Marechal, J.C., Sarma, M.P., and Ahmed, S., Establishment of earth tide effect on water-level fluctuations in an unconfined hard rock aquifer using spectral analysis, *Curr. Sci.*, 2002, vol. 83, no. 1, pp. 61–64.

Molodenskii, S.M., On local anomalies in the amplitudes and phases of tidal tilts and strains, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1983, no. 1, pp. 3–19.

Molodenskii, S.M., On local anomalies in the amplitudes and phases of tidal tilts and strains, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1987, no. 7, pp. 3–9.

Molodenskii, S.M., On the effect of oceanic tides on the inertial coupling between the liquid core and the mantle, *Izv., Phys. Solid Earth*, 2006, vol. 42, no. 5, pp. 357–361.

Molodenskii, S.M. and Molodenskaya, M.S., Resonance of liquid core according to the data of tidal gravity observations in Talgar, *Izv., Phys. Solid Earth*, 2009, vol. 45, no. 10, pp. 839–844.

Morgounov, V.A., Boyarsky, E.A., and Stepanov, M.V., Earthquakes and tidal phases, *Izv., Phys. Solid Earth*, 2005, vol. 40, no. 1, pp. 71–85.

Moussa, M.M. and El-Arabi, A.-G.M., Soil radon survey for tracing active fault: a case study along Qena-Safara road, Eastern Desert, Egypt, *Radiat. Meas.*, 2003, vol. 37, pp. 211–216.

Nikolaev, V.A., Relation between seismicity and phases of multiple and difference frequencies tidal waves, *Dokl. Earth Sci.*, 1996, vol. 349, no. 6, pp. 979–984.

Revuzhenko, A.F., *Prilivnye volny i napravlennyi perenos mass Zemli* (Tidal Waves and Directed Transport of the Earth's Masses), Novosibirsk: Nauka, 2013.

Rykunov, L.N., Khavroshkin, O.B., and Tsyplakov, V.V., Modulation of high-frequency microseisms, *Dokl. Akad. Nauk SSSR,* 1978, vol. 238, no. 2, pp. 303–306.

Rykunov, L.N., Khavroshkin, O.B., and Tsyplakov, V.V., Time variations in the high-frequency seismic noise, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1979, no. 11, pp. 72–77.

Rykunov, L.N., Khavroshkin, O.V., and Tsyplakov, V.V., Lunisolar tidal periodicities in the spectral lines of time variations of high-frequency microseisms, *Dokl. Akad. Nauk SSSR*, 1980, vol. 252, no. 2, pp. 577–579.

Saltykov, V.A., The features of the relationship between high-frequency seismic noise and lunisolar tides, *Dokl. Akad. Nauk*, 1995a, vol. 341, no. 3, pp. 406–407.

Saltykov, V.A., The probable mechanisms of the influence of Earth's tides on the high-frequency seismic noise, *Vulkanol. Seismol.*, 1995b, no. 3, pp. 81–90.

Saraev, A.K., Pertel, M.I., and Malkin, Z.M., Correction of the electromagnetic monitoring data for tidal variations of apparent resistivity, *J. Appl. Geophys.*, 2002, vol. 8, nos. 1–2, pp. 91–100.

Sheremet'eva, O.V. and Smirnov, S.E., Tidal components of geomagnetic variations, *Geomagn. Aeron.*, 2007, vol. 47, no. 5, pp. 588–597.

Sheremet'eva, O.V., Components of geomagnetic variations with tidal wave frequencies, *Geomagn. Aeron.*, 2011, vol. 51, no. 2, pp. 221–225.

Shilo, N.A. and Vashilov, Yu.A., Earth's tides as a tectonic pump and vibrator, *Dokl. Akad. Nauk SSSR*, 1989, vol. 307, no. 4, pp. 833–836.

Shlien, S., Earthquake–tide correlation, *Geophys. J. Roy. Astron. Soc*, 1972, vol. 28, pp. 27–34.

Shpynev, B.G., Oinats, A.V., Lebedev, V.P., Chernigovskaya, M.A., Orlov, I.I., Belinskaya, A.Yu., and Grekhov, O.M., Manifestation of gravitational tides and planetary waves in long-term variations in geophysical parameters, *Geomagn. Aeron.*, 2014, vol. 54, no. 4, pp. 500–512.

Sidorenkov, N.S., *Fizika nestabil'nostei vrashcheniya Zemli* (The Physics of Instability in the Earth's Rotation), Moscow: Nauka, 2002.

Sidorenkov, N.S., Celestial-mechanical factors of the weather and climate change, *Geofiz. Protsessy Biosfera*, 2015, vol. 14, no. 3, pp. 5–26.

Soloviev, S.P. and Spivak, A.A., Electromagnetic effects during relaxation processes in the Earth's inhomogeneous crust, *Dokl. Earth Sci.*, 2007, vol. 417, no. 9, pp. 1449–1453.

Soloviev, S.P. and Spivak, A.A., Electromagnetic signals generated by the electric polarization during the constrained deformation of rocks, *Izv., Phys. Solid Earth*, 2009, vol. 45, no. 4, pp. 347–355.

Spivak, A.A., The specific features of geophysical fields in the fault zone, *Izv., Phys. Solid Earth*, 2010, vol. 46, no. 4, pp. 327–338.

Spivak, A.A., Rigidity of the fault zones in the Earth's crust estimated from seismic data, *Izv., Phys. Solid Earth*, 2011, vol. 47, no. 7, pp. 600–609.

Spivak, A.A., Rigidity of tectonic structures in the Central East European Platform, *Dokl. Earth Sci.*, 2006, vol. 410, no. 7, pp. 1083–1086.

Spivak, A.A. and Kishkina, S.B., The use of microseismic background for the identification of active geotectonic structures and determination of geodynamic characteristics, *Izv., Phys. Solid Earth*, 2004, vol. 40, no. 7, pp. 573–586.

Spivak, A.A. and Khazins, V.V., Variation in fracture zone rigidity by dynamic effects, *Dokl. Earth Sci.*, 2013, vol. 449, no. 1, pp. 328–331.

Spivak, A.A. and Kozhukhov, S.A., Spatiotemporal natural radon variations in the subsoil atmosphere, *Dokl. Earth Sci.*, 2004, vol. 395, no. 2, pp. 223–225.

Spivak, A.A., Kishkina, S.B., and Kharlamov, V.A., Precessional motions of structural blocks of the Earth's crust, *Dokl. Earth Sci.*, 2009a, vol. 427, no. 5, pp. 830–832.

Spivak, A.A., Kozhukhov, S.A., Sukhorukov, M.V., and Kharlamov, V.A., Radon emanation as an indicator of the intensity of intergeospheric interactions at the Earth's crust–atmosphere interface, *Izv., Phys. Solid Earth*, 2009b, vol. 45, no. 2, pp. 118–133.

Starzjinsky, S.S., Studying the dynamics of the lunar daily geomagnetic variations, *Geomagn. Aeron.*, 2008, vol. 48, no. 2, pp. 265–276.

Tanaka, S., Masakazu, O., and Hario, S., Evidence for tidal triggering of eathquakes as revealed from statistical analysis of global data, *J. Geophys. Res.*, 2002, vol. 107, no. B10, pp. 2211–2215.

Tektonicheskaya rassloennost' litosfery i regional'nye geologicheskie issledovaniya (Tectonic Stratification of the Lithosphere and Regional Geological Studies), Baranov, G.I., Belov, A.A., Burtman, V.S, Dobrzhinetskaya, L.F., Dotduev, S.I., Zinkevich, V.P., Zlobin, V.L., Knipper, A.L., Kurenkov, S.A., Lobkovskii, L.A., Luk'yanov, A.V., Mazarovich, A.O., Makarov, V.I., Markov, M.S., Perfil'ev, A.S., Puishcharovskii, Yu.M., Rachkov, V.S., Rikhter, A.V., Rozen, O.M., Ruzhentsev, S.V., Savel'eva, G.N., Samygin, S.G., Sokolov, S.D., Trifonov, V.G., and Shcherba, I.G., Moscow: Nauka, 1990.

Tereshchenko, E.D., Sidorenkov, A.E., and Grigor'ev, V.F., Tidal effects in the controlled-source ULF electromagnetic field on the Baltic crystalline shield, *Izv., Phys. Solid Earth,* 2014, vol. 50, no. 1, pp. 112–117.

Utkin, V.I., Mamyrov, E., Kan, M.V., Krivasheev, S.V., Yurkov, A.K., Kosyakin, I.I., and Shishkanov, A.N., Radon monitoring in the Northern Tien Shan with application to the process of tectonic earthquake nucleation, *Izv., Phys. Solid Earth*, 2006, vol. 42, no. 9, pp. 775–784.

Wenzel, H.-G., Earth tide data processing package ETERNA 3.20, *Bulletin d'Informations Marees Terrestres, Bruxelles*, 1994, vol. 120, pp. 9019–9022.

Widrow, B. and Stearns, S.D., *Adaptive Signal Processing*, Englewood Cliffs, New Jersey: Prentice-Hall, 1985.

Yurkov, E.F. and Gitis, V.G., Relation between seismicity and phases of tidal waves, *Izv., Phys. Solid Earth*, 2005, vol. 40, no. 4, pp. 255–266.

Zhamaletdinov, A.A., Mitrofanov, F.P., Tokarev, A.D., and Shevtsov, A.N., The influence of lunar and solar tidal deformations on electrical conductivity and fluid regime of the Earth's crust, *Dokl. Earth Sci.*, 2000, vol. 371, no. 2, pp. 403–407.

Zurbenko, I.G. and Potrzeva, A.L., Tidal waves in the atmosphere and their effects, *Acta Geophys.*, 2009, vol. 58, no. 2, pp. 356–373.

Translated by M. Nazarenko