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Neutron Generation and Geomagnetic Disturbances in Connection with the Chilean Earthquake of February 27, 2010 and a Volcanic Eruption in Iceland in March–April 2010

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Abstract—The relationship between solar and geomagnetic activities in connection with seismicity and volcanic eruptions on the globe during the period 1680–2010 is studied. The centennial cycles of terrestrial endogenous activity, related to solar and geomagnetic activity, are revealed; at the beginning of these cycles, solar cycles with small Wolf numbers were detected, while intensive seismic and volcanic activity was observed for several decades. A stable negative correlation between seismicity and volcanism, on the one hand, and solar and geomagnetic activity, on the other hand, were found. Experiments, which were simultaneously carried out at the Pushkov Institute of Geomagnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow oblast, and the Karymshina Complex Geophysical Observatory, Kamchatka Branch, Geophysical Survey, Russian Academy of Sciences, have verified the suggestion that disturbances in the geomagnetic field and neutron generation occur during the early stages of strong earthquakes. It is supposed that the mechanism of primary generation of terrestrial neutrons is related to nuclear reactions in the Earth's interior.

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1. INTRODUCTION

It is known that a change in solar activity causes a chain of mutually linked phenomena in the interplanetary space, magnetosphere, ionosphere, neutral atmosphere, and the biosphere. The influence of solar activity on animate and inanimate objects of the Earth can be represented as follows: disturbance on the Sun (a powerful flare); disturbance in the interplanetary space (increase in the concentration and velocity of the solar wind and changes in magnetic field parameters); disturbance in the magnetosphere and plasmasphere (magnetic storm); and, finally, changes in cosmic ray paths in the vicinity of the Earth, changes in the atmospheric circulation, followed by weather changes and other natural phenomena related to variations in the intensity and spectrum of terrestrial electromagnetic fields, which lead to shifts in psychological and physiological parameters of organisms (Shestopalov and Kharin, 2006).

An analysis of publications on the relationship between solar activity and seismicity has indicated that conclusions change depending on the quality and completeness of the catalogs used and the duration of observations: researchers either claim a correlation between earthquake energy and Wolf numbers or find an anticorrelation between them (Sytinskii, 1989; Georgieva, Kirov, and Atanasov, 2002; Lotsinskaya, 1999). Thus, one of the aims was to compile the most complete and homogeneous catalogs of earthquakes for a long-term period in order to assess the relationship between earthquake energy and solar activity.

In addition to seismicity, one of the main manifestation forms of the Earth's endogenous activity is volcanism. It is studied from different aspects in many publications; the "Global Volcanism" program is carrying out (http://www.volcano.si.edu/world/). Spatial distributions of earthquakes and volcanic eruptions were considered in (Levin and Chirkov, 1999; Bulatova, 2005; Fedorov, 2002; Khain and Khalilov, 2009).

Annual synchronicity in seismicity and volcanism manifestations with a peak in June–July was revealed in (Belov, 1986).

In our investigations, on the basis of long-term statistical data, we studied the relationship between the endogenous activity of the Earth (earthquakes and volcanism) and solar and geomagnetic activity (Sobolev, Shestopalov, and Kharin, 1998; Shestopalov and Rogozhin, 2005; Shestopalov and Kharin, 2006; Belov, Shestopalov, and Kharin, 2009; Kharin, Belov, and Shestopalov, 2010; Belov et al., 2010).

These studies are based on the following points:

(a) The Sun, interplanetary space, magnetosphere, ionosphere, the Earth's atmosphere, other geospheres, and the Earth itself with processes in its interiors, leading to earthquakes and other phenomena, are an entire physical system (i.e., seismic and volcanic phenomena are parts of an integrated physical process in the Sun–Earth system).

(b) Processes in the Sun–Earth system are interrelated, and the state of every component affects physical and other processes within the system.

(c) Seismic and volcanic phenomena are determined by both terrestrial and solar processes. Experiments carried out in the outer space and on the Earth (Hanel, Conrath, and Herath, 1981; Hanel, Conrath, and Kunde, 1983; Pollack et al., 1986; Pollack, Hurter, and Johnson, 1993) enabled scientists to discover that the Earth and other large planets, as well as the Sun, have their own internal energy sources. This indicates the presence of natural endogenous activity of the Earth, mainly manifested as tectonic and seismic processes.

The present work continues this investigation. The main aim is to verify the recording of neutrons, which are related to earthquakes and volcanic eruptions, on the Earth's surface.

2. CENTENNIAL CYCLES OF SOLAR ACTIVITY, TERRESTRIAL SEISMICITY, AND VOLCANISM

To investigate the relationship between solar activity and seismicity and volcanism on the Earth, we analyzed data on seismic and volcanic energy released from earthquake foci and volcanic eruptions on the globe for the period from 1680 until 2010 and compared them with the solar activity cycles.

For the present work, we compiled a catalog of earthquakes with $Ms \geq 6$ and $mb \geq 5.5$, which incorporated the data from the National Earthquake Information Center, US Geological Survey (http://neic.usgs.gov), and the International Seismological Center (http://www.isc.uk). The earthquake energy was calculated by the formula $\log E = 11.8 + 1.5Ms$ for earthquakes the epicenters of which were at depths less than 100 km and $\log E = 5.8 + 2.4mb$ for earthquakes the epicenters of which were at depths of more than 100 km.

Analyzing the Earth's volcanism, we used data on volcanic eruptions from the catalog of the Smithsonian Institution's "Global Volcanism Program" (http://www.volcano.si.edu/world/). On this basis, we created a general world database including the volumes of erupted lava and ash (in km^3). Since the used catalog of eruptions did not contain data on eruption energy, this parameter was estimated on the basis of the correlation found by the authors when analyzing the catalog by I.I. Gushchenko (1979); this correlation links the volume of ejected ash and the energy of an eruption. On the basis of these data, we revealed centennial cycles (about 100 years long) of solar activity, terrestrial seismicity, and the Earth's endogenous activity (including volcanic activity). At the beginning of each of three complete centennial cycle (i.e., in the late 17th–early 18th, late 18th–early 19, and late 19th–early 20th centuries), the seismic and volcanic activities were maximal, while the Wolf numbers characterizing solar activity were minimal. Thus, there was an obvious negative correlation between the seismicity and volcanism of the Earth and solar activity; i.e., the most intensive seismic and volcanic activity was observed during insignificant solar activity and vice versa.

Taking the most complete and valid data for the period 1888–2010, it is reasonable to consider the elements of centennial variations in seismic and volcanic components of terrestrial endogenous activity in more detail. An example will be the 20th century cycle (Fig. 1).

As is seen, seismicity grew rapidly in the late 19th century, reached its peak in the early 20th century, and then decreased gradually in intensity (see Figs. 1b, 1c). Note that the shape of the curve for variations in the numbers of $M \geq 8$ earthquakes is similar to that of the curve for the level of energy release during earthquakes. This is caused by the fact that the total seismic energy is predominantly determined by great earthquakes. Minimal values of seismic activity had been observed just before 1990 (i.e., approximately 100 years after intensity growth started). Solar activity in periods of maximal seismic energy release (in the early 20th century) had the lowest values during the whole 20th century (see Fig. 1a). Solar activity gradually intensified throughout the century, and its highest smoothed values were in the 1950s and 1980s. These solar activity peaks correspond to a relatively low level of seismic energy release. Generally, we found a negative correlation between these parameters with the factor $(r) = -0.8$. This allows us to state that the maximal level of seismicity usually takes place during minimal solar activity and vice versa.

In the present work, on the basis of the created database, we compared maximal energy releases for volcanic and seismic events. This comparison leads us to the conclusion that the maximal level of energy release occurs when a volcanic eruption exceeds the maximal seismic energy release by about an order of magnitude. Therefore, we can assume that the magmatic chambers of volcanoes are the most capacitive energy carriers, i.e., a kind of "heavy artillery" that "shoots" at late stages of the tectonic–magmatic process, as is verified by geological practice.

When seismicity and volcanism graphs are compared, it is remarkable that volcanic activity peaks are delayed by several years relative to seismicity peaks. Generally, the centennial volcanism cycle becomes slightly shifted in time (by approximately one solar activity cycle). Such a small delay of volcanism relative to seismicity may indicate that the seismic process is a

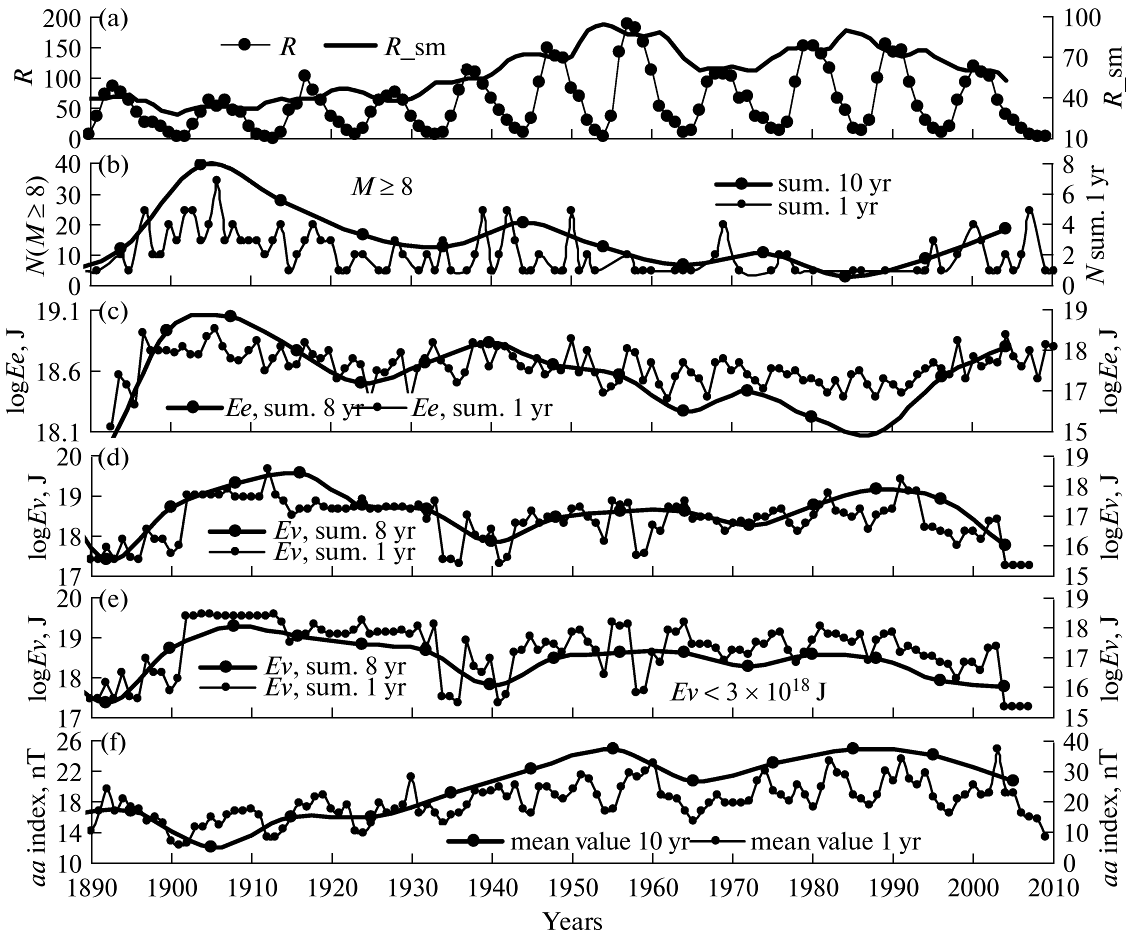

Fig. 1. Temporal variations in 1890–2010: (a) mean annual values of Wolf numbers (R, left-hand side scale) and smoothed ones based on 11 values (Rsm, right-hand side scale); (b) the number of $M \geq 8$ earthquakes per year (right-hand side scale) and for 10 years (left-hand side scale); (c) summarized annual values of earthquake energy on the globe (right-hand side scale) and those for 8 years (left-hand side scale); (d) summarized annual values of volcanic eruption energy on the globe (right-hand side scale) and those for 8 years (left-hand side scale); (e) energy of volcanic eruptions with $E < 3 \times 10^{18}$ J on the globe; (f) mean annual values of the *aa* index (right-hand side scale) and the *aa* index mean values for 10 years (left-hand side scale).

more "short-term response" of the geological medium to processes in the Earth's interiors.

It is seen in Fig. 1 that there is generally a negative correlation between solar activity and the energy of volcanic eruptions. The figure shows that the highest negative correlation ($r = -0.87$) is observed for volcanic eruptions, the energy of which is comparable with the energy release during an earthquake (see Fig. 1e). For all eruptions, this correlation is much lower.

In addition to the above-said, there is a positive correlation ($r = 0.71$) between energy release during earthquakes and that during volcanic eruptions, so direct evidence in favor of the natural unity between tectonic and magmatic processes is obtained.

It had been shown earlier (Shestopalov and Kharin, 2006) that the 100-year cycle of solar and seismic activity is subdivided into three periods of 33 years in length (approximately three 11-year solar activity cycles). It is interesting that the peculiarities of volcanic energy release suggest both the presence of a centennial cycle of volcanism and the subdivision of this cycle into three analogous periods (see Figs. 1d, 1e).

It was noted in (Shestopalov and Kharin, 2006; Belov, Shestopalov, and Kharin, 2009; Belov et al., 2010) that the strongest earthquakes occurred at the beginning of every centennial cycle. According to our data, the third (counting from 1680) cycle started in 1890 and ended in the late 20th century. This suggests that the 1990s were the beginning of a new centennial cycle, which was to be characterized by a relatively low solar activity level and intensive seismic and volcanic activities tending to preserve for approximately the first third of the cycle. The earthquakes on December 26, 2004 ($M = 9$), and March 28, 2005 ($M = 8.6$), near Indonesia; $M > 8$ events in 2006 and 2007; and the recent seismicity of 2008–2011 verify this conclusion. The $M = 8.8$ Chilean earthquake on February 27, 2010, and the Tohoku earthquake on March 11, 2011, continued the list of the strongest events which were predicted to occur at the beginning of the new centennial cycle. Note that the trend in the earthquake energy graph observed around 1890 is similar to the rapid growth in seismic energy release from a minimum in 1990 to a very high level in 2004–2011.

In fact, as has been mentioned, the centennial cycles of volcanic and solar cycles are shifted in time relative to the seismic one by several years. Therefore, the new centennial solar cycle starts after the 23th solar activity cycle.

3. GEOMAGNETIC ACTIVITY AND SEISMICITY OF THE EARTH

The most representative index of geomagnetic activity is *Ap* which describes the average diurnal planetary equivalent amplitude of the terrestrial magnetic field's disturbance. This parameter is determined using a special-purpose network of midlatitude observatories, but it has been recorded since 1932. Therefore, we used the *aa* index, which reflects the average diurnal equivalent amplitude determined by two antipodal observatories (Greenwich and Melbourne) and has been recorded since 1867 (see Fig. 1f).

Figure 1f shows that the *aa* index and the Wolf number were growing throughout the whole studied period, while seismic activity was decreasing. In other words, there is a negative correlation between the *aa* index and seismic activity ($r = -0.8$) (see Figs. 1b, 1c), while a positive correlation exists between the *aa* index and Wolf numbers ($r = 0.8$) during the studied period. A high negative correlation between the *aa* index and volcanic activity is only observed for eruptions comparable with earthquakes in energy (see Figs. 1e, 1f).

Thus, there is a significant negative correlation between seismic energy and solar and geomagnetic activity. A negative correlation between volcanic energy and solar and geomagnetic activity is not observed for all eruptions.

4. NEUTRONS OF TERRESTRIAL ORIGIN

It is known that the interaction between cosmic radiation and air atom cores in the atmosphere produces neutrons in a broad energy spectrum: from thermal to primary space particle energy. Another source of neutron generation is the Sun. Neutrons can emerge during solar flares, resulting from interactions between accelerated particles and different atomic cores of the solar atmosphere. In order to record cosmic radiation and proton fluxes generated during intensive flares, a network of neutron monitors was organized on the Earth's surface in the 1950s (Dorman, 1963). A series of experimental observations in recent years has shown that seismic activity can lead to the formation of neutrons (Kuzhevskii, Shestopalov, and Petrov, 1993; Sobolev, Shestopalov, and Kharin, 1998; Shestopalov and Kharin, 2006; Shestopalov et al., 2011). Based on observations carried out simultaneously by satellites and on the Earth, it has been found that variations in space rays, recorded by neutron monitors on the Earth during disturbances in the interplanetary medium, are determined by both solar processes and phenomena in the geomedium during earthquakes; i.e., neutron monitors installed on the Earth's surface record both space and solar particles and those of terrestrial origin. The energy spectrum of these neutrons covers a range from thermal to fast. The conclusion about the presence of terrestrial neutrons has been verified by S. Yasunaga (1993) who has shown that neutron fluxes are intensified prior to earthquakes and volcanic eruptions by several times compared to reference measurements carried out in relatively quiet (in the geodynamic sense) areas. The Research Institute of Nuclear Physics, Moscow State University, has been carrying out investigations in the Earth's atmosphere using balloon probes for several years; resulting from these studies, anisotropy of thermal neutron fluxes has been revealed (Kuzhevskii, Nechaev, and Shavrin, 1995). It has been found that at altitudes up to 3–5 km a neutron flux directed from the Earth exceeds significantly that directed towards the planet (the mean value of anisotropy at this altitude was 0.6 ± 0.2). These results have allowed one to suppose that there is a thermal neutron field near the Earth's crust, and the parameters of this field are likely determined by the Earth's endogenous activity.

4.1. Neutron Flux and Gamma Radiation Observation Results with Respect to the M_W 8.8 Chilean Earthquake of February 27, 2010, and the Eyjafjallajökull Volcano Eruption in March–April 2010

Experiments that were simultaneously carried out in Moscow oblast and Kamchatka krai have verified the recording of earthquake- and eruption-related neutrons on the Earth's surface (Belov and Shestopalov, 2010; Shestopalov et al., 2011).

(a) Measurements of thermal and fast neutrons, as well as gamma radiation, were carried out by the instruments installed in the experimental chamber of the Cosmic Rays Research Division, Pushkov Institute of Geomagnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow oblast. The technical specifications of the instruments are given below.

• The installation for recording thermal neutrons consists of 15 gas discharge counters of the SI-19N type 3 cm in diameter and 22 cm in length, filled with helium-3 (argon is added) at 405.3 kPa; this instrument records thermal neutrons with energies of 0.025 eV with an efficiency of 0.8.

• The installation for recording fast neutrons consists of two blocks. Each block includes 23 helium proportionate thermal neutron counters of the PD 631 type (about 1 m in length) arranged in two rows and surrounded by polyethylene plates of 15 cm in thickness. The efficiency of thermal neutron recording is 80%.

• Gamma radiation detector $\varnothing 63 \times 63$GD consists of a scintillation detector constructed on the basis of crystalline scintillator NaJ(Tl) of $\varnothing 63 \times 63$ m^3 in size.

• All of these instruments have been operating in continuous mode since 2006.

(b) The thermal neutron flux was also measured by an instrument installed at the Karymshina Complex Geophysical Observatory, Kamchatka Branch, Geophysical Survey, Russian Academy of Sciences. The observatory is situated in the intermontane of the Karymshina River at a distance of 50 km from Petropavlovsk-Kamchatsky.

The neutron detector was manufactured at the Research Institute of Nuclear Physics, Moscow State University. It consists of six standard SI-19N neutron counters.

4.1.1. Variations in Neutron Fluxes and Gamma Radiation in February 2010: Analysis of the Measurement Results

An analysis of variations in neutron fluxes and gamma radiation for February 24–28, 2010, is presented below. The study was made with respect to the strong *Mw* 8.8 earthquake of February 27, 2010, at 0634 UT off the coast of Chile 90 km from the town of Concepcion (the depth is 35 km; the coordinates $\varphi = 35.93°$ S and $\lambda = 72.78°$ W; http://earthquake.usgs.gov/earthquakes/eqarchives/). The aim of this study is to verify the suggestion that the Earth's seismic activity can generate neutrons and other particles and the increase in these fluxes prior to an earthquake can be observed at great distances from the earthquake focus. The present work also presents data on geomagnetic disturbances which were observed during the discussed period. For this purpose, we used data on the terrestrial magnetic field from the Intermagnet global network (about 100 stations; http://intermagnet.org/). Note that after a long-term period of minimal solar activity in 2008–2009, 2010 is the first year of the new 24th solar cycle.

Figure 2 presents values of the *Kp* index that characterizes magnetic activity on a planetary scale. It can be seen that all values of this index are small and there were no magnetic storms in the given period.

The same figure contains minute intensity values for thermal and fast neutrons; gamma radiation levels recorded in Troitsk, Moscow oblast; the intensity of thermal neutron fluxes recorded at the Karymshina obervatory in Kamchatka; and the magnitudes of earthquakes that occurred on February 24–28, 2010. Particle flux intensity I expressed in percentages was determined by the formula $I = (Ni - Nb)/Nb \times 100\%$, where Ni is the minute values of particle fluxes and Nb is the background value of the particle flux observed on February 24.

It is seen in Fig. 2 that approximately two days prior to the earthquake of February 27 (i.e., on late February 24–early February 25) significant bursts in the intensity of thermal and fast neutrons and gamma radiation began to be recorded in Moscow (Figs. 2d–2f). Here the minute values of their fluxes are given in Fig. 2. Based on the minute data, the maximal amplitude of thermal neutrons for this period was about 5000%; that of fast neutrons, about 2000%; and that of gamma radiation, about 800%. It is seen in Fig. 2 that intensive bursts of particles were observed both prior to the earthquake of February 27 and after it. It is also seen that the characters of variations in the intensity of thermal neutrons are different for Moscow and Kamchatka. The principal peculiarity of variations in thermal neutrons for Kamchatka is that the intensity of neutrons began to grow from several tens of percentage points approximately a day before the earthquake and this growth reached its peak (about 100000%) six hours before the earthquake; i.e., intensity grew from a minimal to a maximal value by several orders of magnitude (see Fig. 2c) and then, after the peak value, the intensity of particles dropped rapidly, reaching background values when the earthquake was occurring.

Let us show that the period preceding the Chilean earthquake was also characterized by disturbances in the terrestrial magnetic field.

Figure 3 presents variations in the magnetic field observed on February 24. Variations in the intensity of thermal neutrons observed in Kamchatka are also presented here. It is seen that in the first half of February 24 thermal neutron intensity bursts were recorded in Kamchatka. Also note that growth in neutron fluxes was not recorded at IZMIRAN at the time.

Let us consider the peculiarities of the character of variations in the terrestrial magnetic field intensity at this time. Figure 3 presents variations in the terrestrial magnetic field (the *Bx* component) recorded at stations where significant disturbances were observed in the period before the Chilean earthquake on February 27 (i.e., approximately three days before the earthquake). All of these stations were situated in the Western Hemisphere of the Earth; their codes and geographic coordinates are denoted in Figs. 3b–3i. The arrows in this figure indicate disturbance peaks. The maximal disturbance amplitude ($Bx = -690$ nT) was observed at the BLC station, Baker Lake, Canada (64.3° N, 96° W); the duration of this disturbance was about an hour. Significant disturbances were also observed at the following stations: YKC, Yellowknife, Canada (62.5° N, 114.5° W; $Bx = -178$ nT); NAG, Narsarsuag, Denmark (61.2° N, 45.4° W; $Bx = -160$ nT); and FCC, Fort Churchill, Canada (58.8° N, 94° W; $Bx = -267$ nT). In the Southern Hemisphere, the maximal disturbance amplitude ($Bx = -200$ nT) was observed at MAW, Mawson, Australia (67.5° S, 62.9° E). As was noted above, the situation in the magnetosphere during the discussed period was quiet (without magnetic storms).

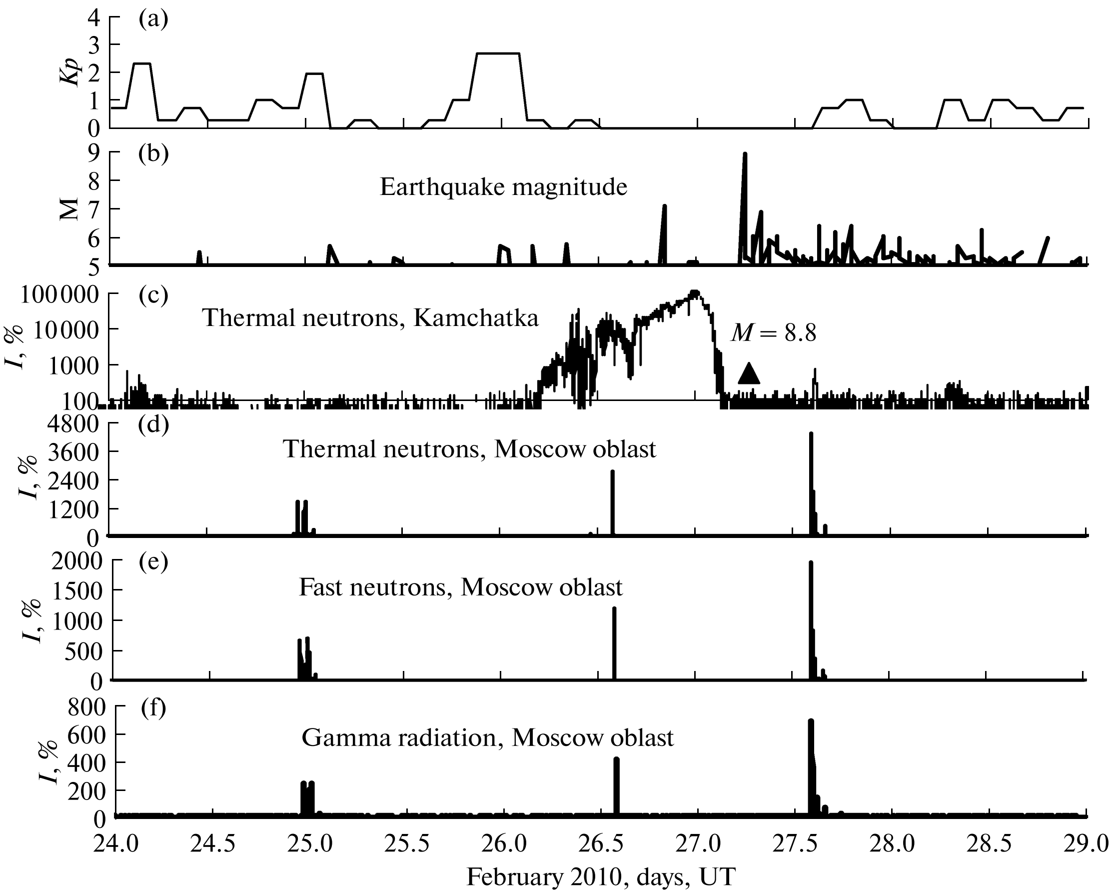

Fig. 2. Temporal variations in February 24–29: (a) *Kp* index; (b) earthquake magnitude (*M*); (c) thermal neutron flux intensity at the station in Kamchatka; (d) thermal neutron flux intensity recorded at IZMIRAN; (e) fast neutron flux intensity recorded at IZMIRAN; and (f) gamma radiation flux intensity recorded at IZMIRAN.

Nevertheless, in this period, the disturbance amplitude nearly reached the value of an average magnetic storm. It is supposed that these processes are caused by endogenous factors, but the external effect is also probable.

Let us note some other peculiarities associated with the character of variations in the terrestrial magnetic field during this disturbance. The arrows in Fig. 3 indicate disturbance peaks. The solid arrows on the curves in Figs. 3e and 3f, showing the data from the VIC (Victoria, Canada; 48.52° N, 123.42° W) and OTT (Ottawa, Canada; 45.40° N, 75.55° W) stations, respectively, indicate that extrema of these curves had been observed earlier than at high latitudes (in both Northern and Southern hemispheres). The delay of disturbances from moderate to high latitudes is approximately 15 min in both Northern and Southern hemispheres. It can also be noted that, in this case, a disturbance of the magnetic field was observed in a narrow layer. The axis of this layer can be roughly drawn from approximately 100° W in the Northern Hemisphere and from the central meridian in the Southern Hemisphere; i.e., it is tilted relative to the vertical in the direction away from the Earth's revolution axis. The disturbance propagation rate within this layer can be estimated at 5–20 km/s.

4.1.2. Variations in Neutron and Gamma Radiation Fluxes in March–April 2010: Analysis of Measurements

Studies were carried out with respect to the Eyjafjallajökull volcano's eruption in Iceland (φ – 63.38° N, λ – 19.37° W) in April 2010. The volcano is covered with an ice cap of about 100 km^2; the height is 1666 m; and the diameter of the crater is 3–4 km. The previous eruption was reported in 1821. On March 21, 2010, the volcano awoke from dormancy after 200 years, and the main eruption phase started on April 14. The eruption was so powerful that an emergency situation was declared in Iceland. Based on preliminary data, the volume of ejected ash on April 14–18 was at least 0.25 km^3 (http://en.wikipedia.org/wiki/2010_eruptions_of_Eyjafjallajökull). This eruption is one of the largest since 1993 (http://www.volcano.si.edu/world/).

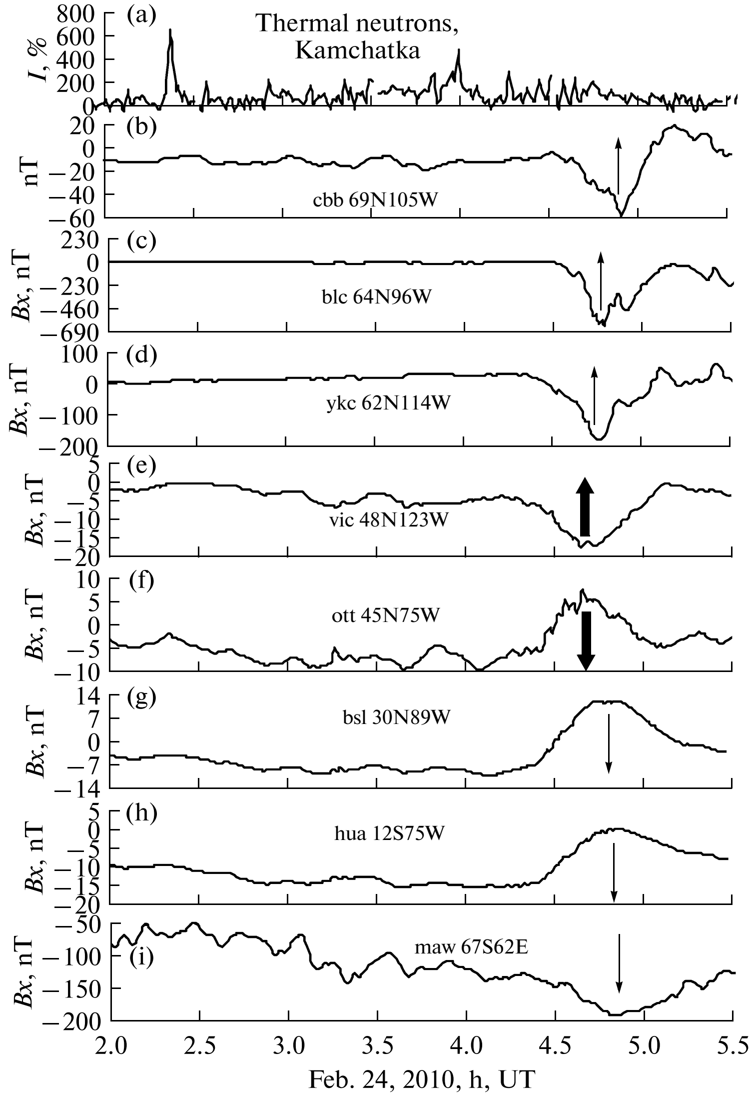

Fig. 3. Temporal variations: (a) neutron intensity recorded at the station in Kamchatka; (b–i) magnetic field intensity amplitudes, the *Bx* component, February 24, 2010.

The time variations in the *Kp* index, neutron fluxes, and the gamma radiation in March–April 2010 are presented in Fig. 4.

It is seen in this figure that both in Moscow oblast and Kamchatka the particle flux had increased by several orders of magnitude several days before the eruption. Based on the IZMIRAN data, intensity bursts of thermal and fast neutrons and gamma radiation were recorded at the beginning of March 2010. According to the data from a station in Kamchatka, growth in the intensity of thermal neutrons started on March 14. On March 17, the particle flux reached a value of 3200 pulses per minute, in contrast to several pulses per minute at the beginning of the month. Thus, the intensity of the thermal neutron flux increased by 80000% three days before the eruption. Based on the IZMIRAN data, the maximal intensity of bursts at the beginning of March 2010 reached ~5000% for thermal neutrons, ~2000% for fast neutrons, and ~800% for gamma radiation.

The main (explosive) eruption phase took place on April 14–18. The neutron and gamma radiation fluxes for this period are given in detail in Fig. 5. The thermal neutron flux in Kamchatka on April 14 began to grow from several to 10000–14000 pulses per minute at the end of the day; i.e., the intensity of the thermal neutron flux in Kamchatka increased by nearly 300000% a day (see Fig. 5b). Based on the IZMIRAN data, in Moscow oblast, the maximal neutron flux was observed on April 18 (i.e., not at the beginning of the explosive phase, but at its end). Let us show that geomagnetic disturbances took place during this volcanic eruption similarly to the period of the Chilean earthquake. Figure 6 presents data on the variations in the

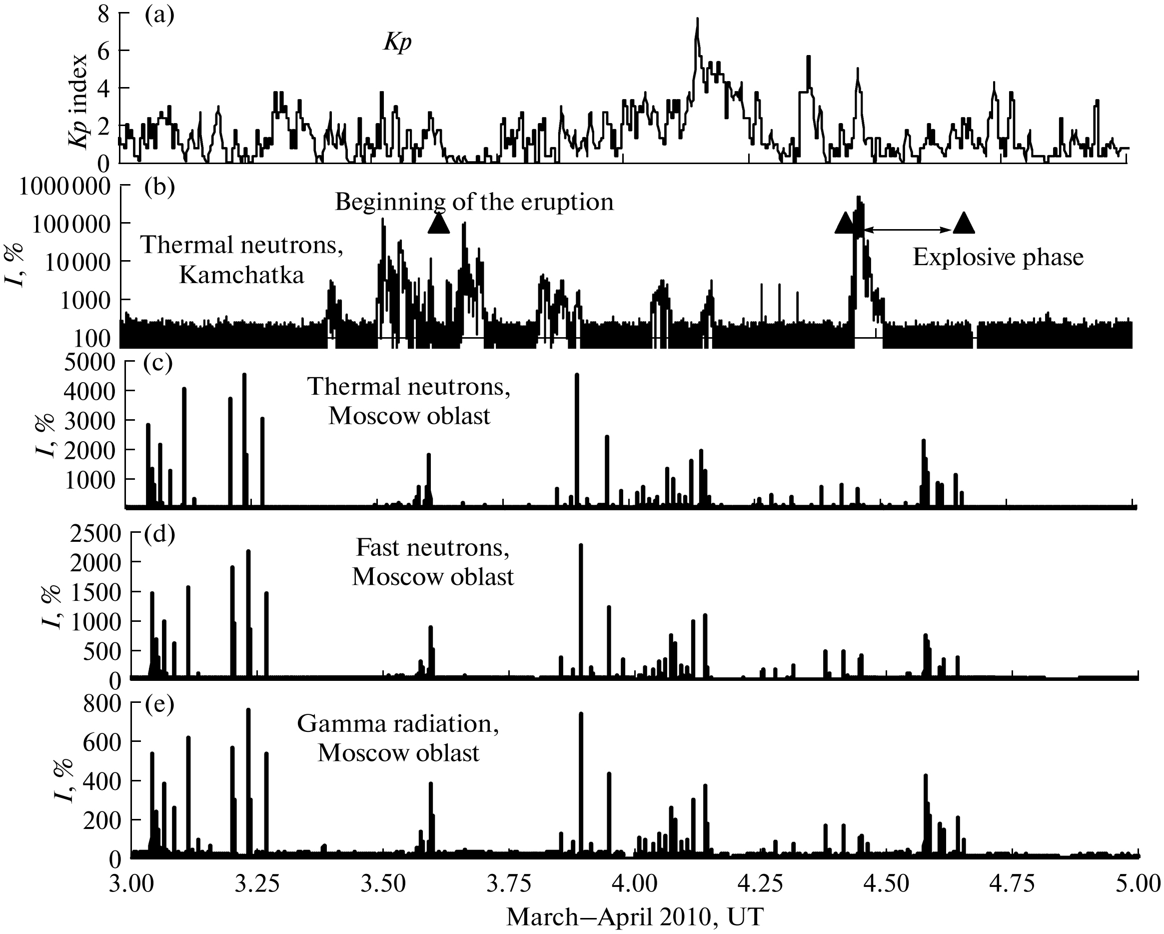

Fig. 4. Temporal variations in March–April 2010 (the abscissa axis contains dates expressed as a decimal fraction of a month): (a) *Kp* index; (b) earthquake magnitude (*M*); (c) thermal neutron flux intensity at the station in Kamchatka; (d) thermal neutron flux intensity recorded at IZMIRAN; (e) fast neutron flux intensity recorded at IZMIRAN; and (f) gamma radiation flux intensity recorded at IZMIRAN. The intensity of the particle flux, I, was determined by the expression $I = (Ni - Nb)/Nb \times 100\%$, where Ni is the minute value of the particle flux and Nb is its background value.

magnetic field for the period April 11–16. The variations in the intensity of the thermal neutron flux recorded at the Kamchatka and IZMIRAN observation points are also presented. It is seen that geomagnetic disturbances were observed prior to and during the explosive phase of the earthquake both in the Northern and Southern hemispheres. Figure 6 also presents variations in the *Bx* component of the terrestrial magnetic field, recorded at stations where a significant disturbance was detected during the explosive eruption phase. The maximal amplitude of disturbances in the *Bx* component was ~1500 nT and was observed at the SOD_X station, Sodankyla, Finland (67° N, 26° E). The duration of this disturbance was about an hour. As is seen in Fig. 5f, significant disturbances in the magnetic field were also observed in the Southern Hemisphere.

Thus, during the preparation of strong earthquakes and large eruptions, disturbances in the terrestrial magnetic field and neutron generation take place and neutrons are recorded in areas far from disaster points.

5. DISCUSSION

The reported facts allow us to suppose that the Earth's seismic and volcanic activity and the generation of particle fluxes can be interrelated. An increase in these fluxes prior to an earthquake is observed even at great distances from the disaster area. To explain the probable mechanisms of neutron generation, the following facts should be taken into consideration.

It is known that strong earthquakes, such as the Chilean (2010) and Sumatran (2004) ones, caused a change in the duration of the day and the orientation of the Earth's revolution axis (http://jpl.nasa.gov/news/index.cfm); i.e., it is obvious that strong earthquakes cause disturbances covering all geospheres of the planet. These disturbances may reflect the drift of the core and its induced vibrations with a broad spec-

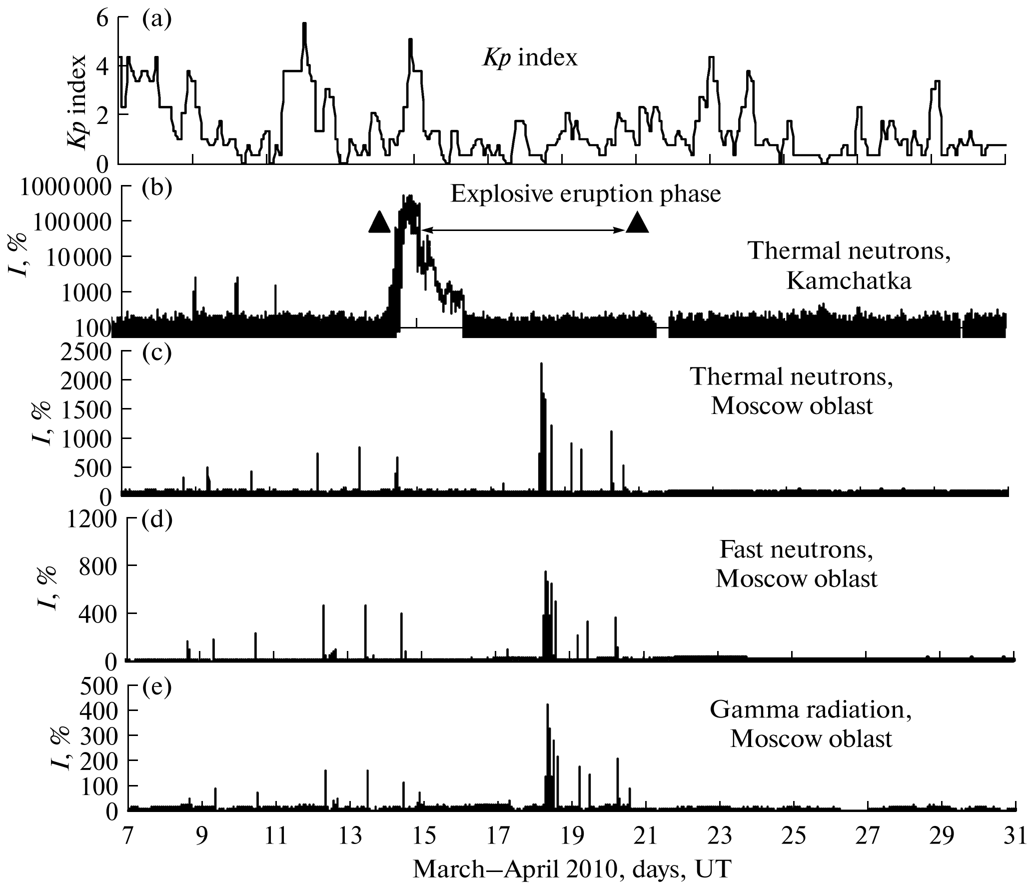

Fig. 5. Temporal variations in April 2010: (a) *Kp* index; (b) thermal neutron flux intensity at the station in Kamchatka; (c) thermal neutron flux intensity recorded at IZMIRAN; (d) fast neutron flux intensity recorded at IZMIRAN; and (e) gamma radiation flux intensity recorded at IZMIRAN. The data on neutrons and gamma rays are in minutes.

trum of frequencies relative to the viscoelastic mantle (Podobed and Nesterov, 1982; Barkin, 2008). At present, many scientists believe that fluctuations in the Earth's revolution should be searched for in interactions between the mantle and the core. It is established in geophysics that the core revolves relative to the mantle at ~0.2° per year. The drift of the core and the intensification of its cyclic displacements are accompanied by elastic deformations of the mantle and respective abrupt changes of the stress and thermodynamical state of all its layers. It has been found (Enikopolov, Mkhitaryan, and Karagezyan, 1986; Sharov, 1990) that the internal energy of a body increases during deformation and matter transforms into a qualitatively new activated state, at which reactions and processes impossible under normal conditions can run. Thus, under a mechanical effect implemented in a plastic domain, the transition of rock material into an activated—ionized state can be achieved. The observed bursts of several minutes in length in fluxes of neutrons and other particles allow us to conclude that processes in the Earth's interior, leading to the generation of particles, run very fast. This means that short-term increases in pressure and temperature, caused by nuclear reactions in the Earth's interiors, can occur in an earthquake hypocenter and in a volcanic chamber prior to an eruption. Investigations of the isotopic composition of helium from diamond deposits of metamorphic complexes in Central Kazakhstan, which, according to these data, were formed due to paleoearthquakes, have shown that the ^{3}He/ ^{4}He ratio reaches unprecedented values of up to 7×10^{-1} (Shukolyukov, Pleshakov, and Semenova, 1996). Another anomalously high value for diamonds was indicated with respect to the concentration of helium isotopes: 2.8×10^{-7} cm^3/g for ^{3}He and ~ 9.2×10^{-4} cm^3/g for ^{4}He. The values of the helium isotopic ratio in 27 South African diamond-bearing kimberlite deposits reach 3.2×10^{-4} (Blyuman, 2003) which is significantly higher than the average planetary content (1.42×10^{-4}) but is close to that of solar helium (4×10^{-4}).

Thus, although paradoxical, earthquakes and volcanic eruptions may create favorable conditions for nuclear reactions, including the presence of deuterium and ^{3}He (Perez, Nakai, and Wakita, 1996).

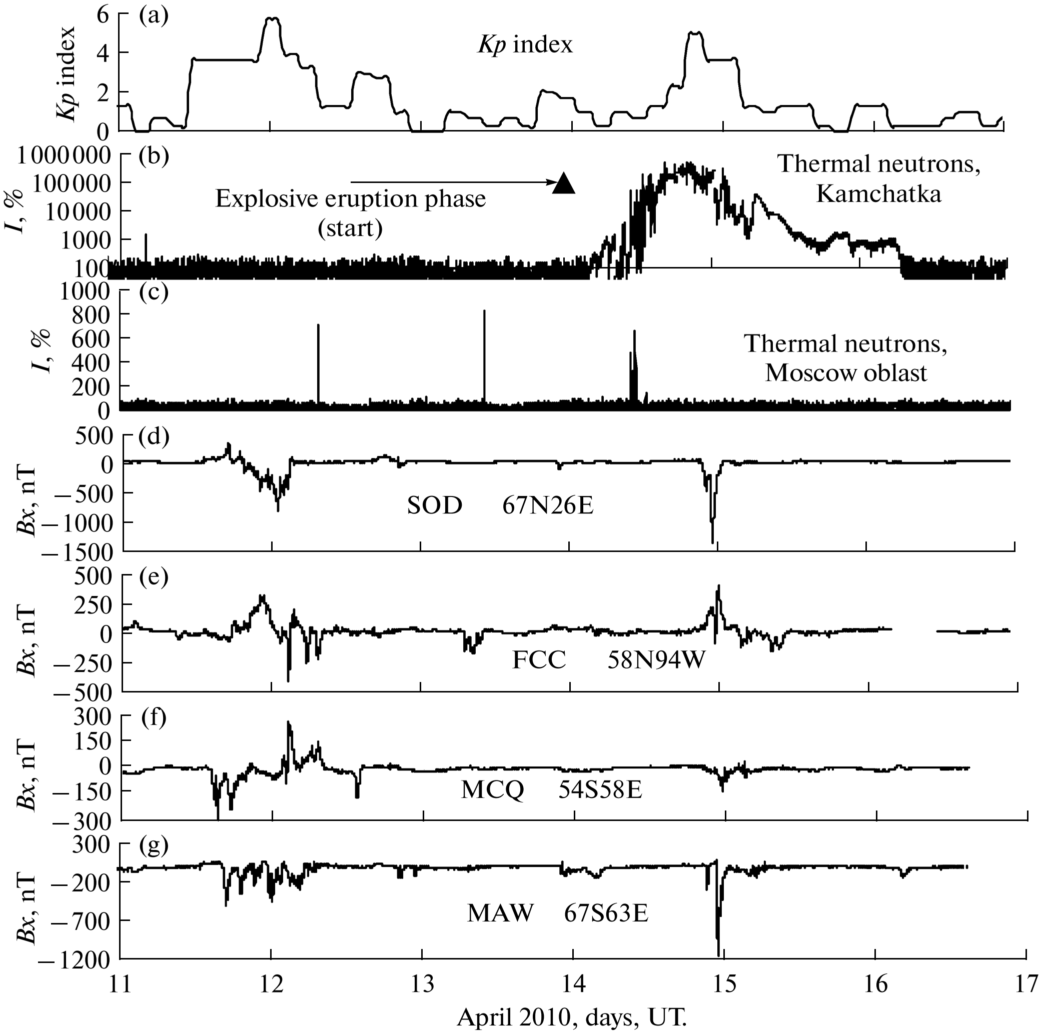

Fig. 6. Temporal variations on April 11–16, 2010: (a, b) thermal neutron flux intensity at the station in Kamchatka), minutes); (c) thermal neutron flux intensity recorded at IZMIRAN, minutes); (d–g) magnetic field intensity amplitudes, the *Bx* component, at different stations (see text for codes).

Hydrogen fluxes from the Earth's core were reported in (Larin, 1980). It is also known that radon, hydrogen, helium, radioactive element content, and total radioactivity in groundwater and thermal spring gases increase sharply by about an order of magnitude prior to earthquakes and volcanic eruptions. Helium in an isolated state is represented by alpha particles that form neutrons when interacting with the material of the upper crust (Kolyasnikov, 1984).

However, the question arises as to how such neutrons reach the Earth's surface without attenuation? In terms of modern concepts, the geophysical medium consists of blocks of different sizes (from very large to very small) (Sadovskii, Bolkhovitinov, and Pisarenko, 1987); i.e., the medium is not continuous but hierarchically discrete. This system is open for energy exchange with the environment and can bound elastic energy, and these properties allow one to consider it as a dynamical energy-containing medium. Activity is the property of such a medium. Temporal changes in rock properties are not related to matter motion, but mostly to changes in the stress–strain state of the geomedium. As a result, energy transfers from one structural element to another in different directions. In the case of a strong disturbance, this process can involve the Earth as a whole. The disturbance front that causes the redistribution of stress reaches the Earth's surface at a certain moment. The appearance of a deformation front that propagates in different directions within the Earth's crust was reported in (sobolev, 1993). The observed distribution of deformation in the geomedium can be interpreted as a process of gradual transmission of tectonic load from one structural element of the geophysical medium to another at a finite rate (Sadovskii, Bolkhovitinov, and Pisarenko, 1987). The nature of deformation waves is unknown. We can suggest that the appearance of a disturbed state in certain structural elements of the geophysical medium produces gravity waves that gradually generate neutrons and other particles in an unknown way; thus, gravity waves promote the transfer and motion of particles, making them reach the Earth's surface.

Since both seismic and volcanic activity of the Earth is a source of neutrons and other particles, the natural unity of the tectonic–magmatic process is directly evidenced. An increase in fluxes of these particles prior to earthquakes and eruptions can be observed at significant distances from the event area and can be used for prediction. For this purpose, instruments recording thermal and fast neutrons should be installed in several active zones in the Northern and Southern hemispheres. As a result, seismic and volcanic hazards can be assessed on a planetary scale and the area of a disaster may be specified if a sufficient number of instruments is available.

6. CONCLUSIONS

1. The peculiarities of variations in seismicity and volcanism allow one to suggest the existence of a general centennial cycle of the Earth's endogenous activity; this cycle is subdivided into three periods of ~33 (30–40) years in length and are related to geomagnetic activity.

2. A significant negative correlation between seismic energy and solar and geomagnetic activity has been found. A negative correlation between volcanic energy and solar and geomagnetic activity has not been observed for all eruptions.

3. The previous seismic centennial cycle started in about 1890 and is thought to have ended in the late 20th century. This suggests that the new centennial cycle started in the 1990s and intensive seismic activity is to be observed at its beginning. The centennial volcanic and solar cycles are shifted in time relative to the seismic one by several years. Similarly to seismic activity, volcanic activity is high at the beginning of a new cycle, while solar activity is low.

4. The M 8.8 Chilean earthquake of February 27, 2010, has continued the list of strong events which are to occur at the beginning of the new cycle of terrestrial endogenous activity. In this sense, the catastrophic earthquake in Japan supports this suggestion.

5. Ground-based measurements of (a) thermal and fast neutrons and gamma radiation, carried out in IZMIRAN, Troitsk, Moscow oblast, and (b) thermal neutrons at the Karymshina Complex Geophysical Observatory in Kamchatka have detected particle fluxes related to the Mw 8.8 Chilean earthquake of February 27 and the Eyjafjallajökull volcano's eruption in March–April 2010.

6. During the preparation of strong earthquakes and intensive volcanic eruptions, disturbances in the geomagnetic field take place with neutron generation detected in areas far from the area of a future disaster.

7. It has been suggested that the mechanism of initial neutron generation is related to nuclear reactions in the Earth's core during the transition of rock material into an activated–ionized state. The recording of neutrons at significant distances from the generation source may be related to neutron transmission by elements of the active hierarchically partitioned geomedium of a wave nature.

8. Since terrestrial seismic and volcanic activity is a source of neutrons and other particles and increases in particle fluxes can be observed at significant distances from their sources, this increase can be used as a precursor for their prediction. For this purpose, instruments recording thermal and fast neutrons should be installed in several active zones in the Northern and Southern hemispheres. However, the problem of specifying where these catastrophic events will occur is still to be solved.

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REFERENCES

Barkin, Yu.V., Secular Polar Drift of the Core during the Present-Day Epoch: Geodynamic and Geophysical Consequences and Confirmations. General and Regional Problems of Tectonics and Geodynamics, *Materialy XLI tektonicheskogo soveshchaniya* (Proc. 41th Tectonic Meeting), 2008, vol. 1, pp. 55–59.

Belov, S.V., Periodicity of Modern and Ancient Volcanic Earth, *Dokl. Ross. Akad. Nauk*, 1986, vol. 291. no. 2, pp. 421–425.

Belov, S.V. and Shestopalov, I.P., Neutron and Gamma-Ray Fluxes as Precursors of Volcanic and Seismic Disasters, *Vestn. Mosk. Gosud. Otkr. Univ., Ser. Tekhn. Tekhnol.*, 2010, no. 2, pp. 62–70.

Belov, S.V., Shestopalov, I.P., and Kharin, E.P., On the Interrelations between the Earth Endogenous Activity and Solar and Geomagnetic Activity, *Dokl. Ross. Akad. Nauk*, 2009, vol. 428, no. 1, pp. 104–108.

Belov, S.V., Shestopalov, I.P, Kharin, E.P., Solov'ev, A.A., and Barkin, Yu.V., Volcanic and Seismic Activity of the Earth: Spatial–Time Regularities and the Relation to Solar and Geomagnetic Activity, *MGOU-XXI. Novye Tekhnologii*, 2010, no. 2, pp. 3–12.

Blyuman, B.A., Solar Helium and Neon in Diamonds, Plume Basalts, and Hot Spots: The Possible Time and Origination of the Lower and Upper Mantle Heterogeneity, *Geokhimiya*, 2003, no. 3, pp. 340–344.

Bulatova, N.P., Latitudinal Distribution of the Earth Seismicity Depending on the Position of the Sun and Moon, *Vulkanol. Seismol.*, 2005, no. 2, pp. 57–78.

Dorman, L.I., *Variatsii kosmicheskikh luchei i issledovanie kosmosa* (Cosmic Ray Variations and Space Research), Moscow: Akad. Nauk SSSR, 1963.

Enikolopov, N.S., Mkhitaryan, A.N., and Karagezyan, A.S., Ultrarapid Reactions of Decay in Solids under Pressure, *Dokl. Akad. Nauk SSSR*, 1986, vol. 288, no. 3, pp. 657–660.

Fedorov, V.M., Specific Features in the Latitudinal Distribution of Volcanic Eruptions, *Vulkanol. Seismol.*, 2002, no. 4, pp. 39–43.

Georgieva, K., Kirov, B., and Atanasov, D., On the Relation between Solar Activity and Seismicity on Different Time Scales, *J. Atmos. Electr.*, 2002, vol. 22, no. 3, pp. 291–300.

Gushchenko, I.I., *Izverzheniya vulkanov mira (katalog)* (Volcanic Eruptions: A Catalog), Moscow: Nauka, 1979.

Hanel, R.A., Conrath, B.J., and Herath, L., Albedo, Internal Heat and Energy Balance of Jupiter: Preliminary Results of the Voyager Infrared Investigation, *J. Geophys. Res.*, 1981, vol. 86, p. 8705 8712.

Hanel, R.A., Conrath, B.J., and Kunde, V.G., Albedo, Internal Heat Flux, and Energy Balance of Saturn, *Icarus*, 1983, vol. 53, pp. 262–285.

Khain, V.E. and Khalilov, E.N., Tsiklichnost' geodinamicheskikh protsessov: ee vozmozhnaya priroda, (Cyclicity of Geodynamic Processes: Its Possible Nature), Moscow: Nauch. Mir, 2009.

Kharin, E.P., Belov, S.V., and Shestopalov, I.P., Spatial–Time Variations in Seismicity of the Earth and Solar Activity, *Sb. Dokl. V Mezhd. Konf. "Solnechno-Zemnye Svyazi i Fizika Predvestnikov Zemletryasenii"* (Proc. 5th Int. Conference Solar–Terrestrial Coupling and Physics of Earthquake Precursors), Paratunka, 2010, pp. 470–473.

Kolyasnikov, Yu.A., On the Possibility of Natural Nuclear Reactions and Geological Processes, *Vulkanol. Seismol.*, 1984, no. 1, pp. 59–70.

Kuzhevskii, B.M., Shestopalov, I.P., and Petrov, V.M., On Prediction of Radiation Conditions in the Interplanetary Space, *Kosm. Issled.*, 1993, vol. 31, no. 6, pp. 89–103.

Kuzhevskii, B.M., Nechaev, O.Yu., and Shavrin, P.I., Anisotropy of Thermal Neutrons in the Atmosphere, *Geomagn. Aeron.*, 1995, vol. 32, no. 2, pp. 166–170.

Larin, V.N., *Gipoteza iznachal'no gidridnoi Zemli* (Initially Hybrid Earth Hypothesis), Moscow: Nedra, 1980.

Levin, B.V. and Chirkov, E.B., Specific Features in the Latitudinal Distribution of Seismicity and the Earth Rotation, *Vulkanol. Seismol.*, 1999, no. 6, pp. 65–69.

Lotsinskaya, N.I., Relation of the Earthquake Global Energy to Solar Activity, *Vestn. Kiev. Univ., Ser. Astron.*, 1999, no. 35, pp. 45–50.

Perez, N.M., Nakai, S., and Wakita, H., Helium-3 Emission in and around Teide Volcano, Tenerife, Canary Islands, Spain, *Geophys. Res. Lett.*, 1996, vol. 23, no. 24, pp. 3531–3538.

Podobed, V.V. and Nesterov, V.V., *Obshchaya astrometriya* (General Astrometry), Moscow: Nauka, 1982.

Pollac, J.B., Rages, K., and Baines, K.H., Estimates of the Bolometric Albedos and Radiation Balance of Uranus and Neptune, *Icarus*, 1986, vol. 65, pp. 442–466.

Pollack, H.N., Hurter, S.J., and Johnson, J.R., Heat Flow from the Earth's Interior: Analysis of the Global Data Set, *Rev. Geophys.,* 1993, vol. 31, no. 3, pp. 267–280.

Sadovskii, M.A., Bolkhovitinov, L.G., and Pisarenko, V.F., *Deformirovanie geofizicheskoi sredy i seismicheskii protsess* (Geophysical Environment Deformation and Seismic Process), Moscow: Nauka, 1987.

Sharov, V.I., Tectonic Earthquake Center from the Position of the Solid Body Strength Kinetic Theory, in *Sovremennaya geodinamika i glubinnoe stroenie territorii SSSR* (Present-Day Geodynamics and Depth Structure of the USSR Territory), Moscow: Nauka, 1990, pp. 79–85.

Shestopalov, I.P. and Kharin, E.P., Time Variations in the Relations between Seismicity of the Earth and Solar Activity Cycles of Different Duration, *Geofiz. Zh.*, 2006, vol. 28, no. 4, pp. 59–70.

Shestopalov, I.P. and Rogozhin, Yu.A., Correlation between Microbiological and Seismic Activity with Regard to the Solar–Terrestrial Coupling and Neutron Flux Generation, *Kosm. Biol. Aviakosm. Med.*, 2005, vol. 39, no. 3, pp. 20–26.

Shestopalov, I.P, Belov, S.V., Solov'ev, A.A., Kharin, E.P., and Kuz'min, Yu.D., On the Generation of Neutrons and Geomagnetic Field Disturbances a Day before the Catastrophic Chilean Earthquake of February 27, 2010, *Vestn. Mosk. Gos. Otkr. Univ., Ser. Tekhn. Tekhnol.*, 2011, no. 1, pp. 66–75.

Shukolyukov, Yu.A., Pleshakov, A.M., and Semenova, L.F., Isotopic Composition of Helium in Diamond-Bearing Metamorphic Rocks in Northern Kazakhstan, *Geokhimiya*, 1996, no. 1, pp. 22–35.

Sobolev, G.A., *Osnovy prognoza zemletryasenii* (Earthquake Prediction Backgrounds), Moscow: Nauka, 1993.

Sobolev, G.A., Shestopalov, I.P., and Kharin, E.P., Geoeffective Solar Flares and Seismic Activity of the Earth, *Fiz. Zemli*, 1998, no. 7, pp. 85–89.

Sytinskii, A.D., On the Relation between Earthquakes and Solar Activity, *Izv. Akad. Nauk SSSR, Fiz. Zemli*, 1989, no. 2, pp. 13–30.

Yasunaga, S., US Patent 5241175, 1993.