Relationship between solar activity and global seismicity and neutrons of terrestrial origin

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The correlation between solar activity and global seismicity in 1680–2012 was studied. The authors discovered the global cycles of seismicity of the Earth, related to solar activity. They observed the solar cycles with a small number of spots, typical for the beginning of secular cycles, and strong seismic activity, which remained high throughout several decades. The scientists established a significant negative correlation between seismicity and solar activity. They revealed an absolute maximum of global seismic activity in the 20th century and discovered spatial-temporal regularities of manifestations of global seismicity. Experiments, which were simultaneously carried out at the Pushkov Institute of Geomagnetism, Ionosphere and Radiowave Propagation (IZMIRAN), Russian Academy of Sciences, Moscow and the Kamchatka Branch of Geophysical Survey, Russian Academy of Sciences, have verified the suggestion that neutron generation occur during the early stages of strong earthquakes. It was supposed that the mechanism of primary generation of terrestrial neutrons is related to nuclear reactions in the Earth's interior. The authors suggested to use an increase of streams of particles before an earthquake for its forecasting. For this purpose it is necessary to install devices for registration of thermal and fast neutrons in several active zones in the Earth's Northern and Southern hemispheres. *KEYWORDS: Solar activity; global seismicity; earthquakes; secular cycles; migration of earthquakes; generation of neutrons; nuclear reactions.*

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1. Introduction

Analysis of different publications has shown that results of research of an influence of solar activity on global seismicity, the number of which has recently grown, depend on the parameters used and the duration of series of observations. Researchers either claim a correlation between parameters of earthquakes and Wolf numbers or find an anticorrelation between them [*Georgieva et al.*, 2002; *Lotsinskaya*, 1999; *Sytinskii*, 1989]. 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.

Our research was based on the data on seismic and solar activity for a long-term period. We studied a correlation between seismic activity of the Earth with solar activity [*Belov et al.*, 2009; *Shestopalov and Rogozhin*, 2005; *Shestopalov and Kharin*, 2006; *Shestopalov et al.*, 2013; *Sobolev et al.*, 1998].

These studies are based on the following points:

- 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;

- Processes in the Sun–Earth system are interrelated, and the state of every component affects physical and other processes within the system;

- Seismic phenomena are determined by both terrestrial and solar processes. Experiments, carried out in the outer space and on the Earth [*Hanel et al.*, 1981, 1983; *Pollack et al.*, 1986, 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, on the Earth's surface.

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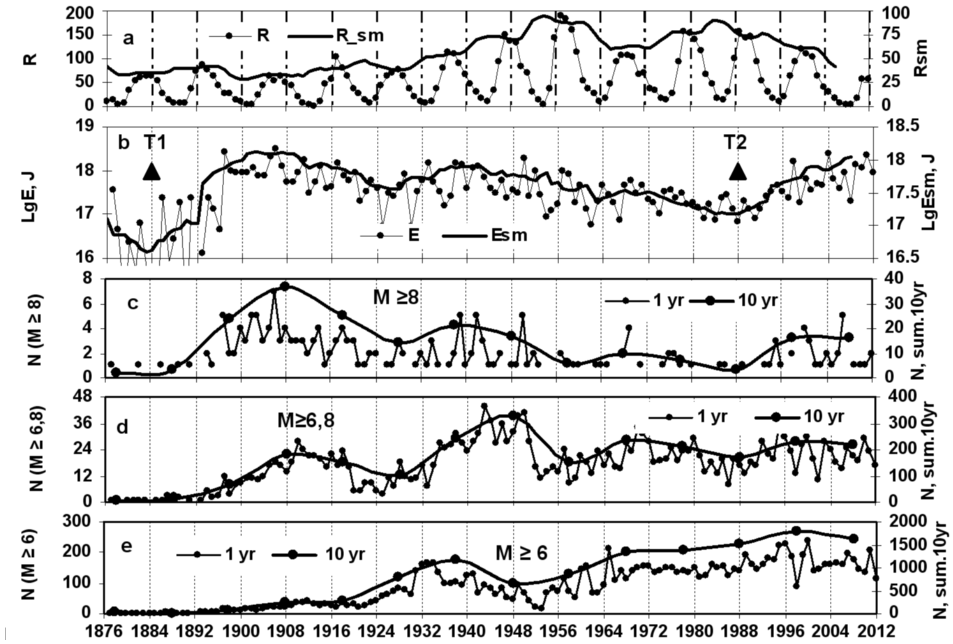

Figure 1. Temporal variations in 1876–2012: a – mean annual values of Wolf numbers (R, left-hand side scale) and smoothed ones based on 11 values (R_{sm}, right-hand side scale); b – summarized annual values (left-hand side scale) and smoothed ones based on 9 values (right-hand side scale) of earthquake energy on the globe; c–d the number of earthquakes per year (left-hand side scale) and for 10 years (right-hand side scale): c – of $M \geq 8$; d – of $M \geq 6.8$; e – of $M \geq 6$. Symbols T1 and T2 on curve b indicate minimal values of seismic energy in a centennial cycle.

2. Centennial Cycles of Solar Activity and Terrestrial Seismicity

To investigate the relationship between solar activity and seismicity of the Earth, in the work [*Shestopalov and Kharin*, 2006] we analyzed data on seismic energy released from earthquake foci 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 $mb \geq 5.5$. It incorporated the databases from the National Earthquake Information Center, US Geological Survey (NEIC, USGS) [http://www.earthquake.usgs.gov/regional/neic/]; the National Geophysical Data Center (NGDC); the Centennial Catalog (Engdahl and Villasenor, 2002) [http://earthquake.usgs.gov/research/data/centennial.php]; the Rothe cathalog of strong earthquakes from 1953 to 1965 [*Rothe*, 1969]. For compiling the catalog for the period 1977–2012 we used the database of earthquakes of the US Geological Survey, containing additional magnitudes and commentaries [http://earthquake.usgs.gov/earthquakes/eqarchives/significant/].

The energy of earthquakes was calculated by using the formula: $\lg E = 11.8 + 1.5\,Ms$ for earthquakes with hypocenters located less than 100 km deep, and by the formula $\lg E = 5.8 + 2.4\,mb$ – for the depths exceeding 100 km.

It should be noted that the method of determining earthquake magnitudes developed over time, therefore different databases include earthquake magnitudes estimated by various methods, and their scales are not always compatible. This factor was taken into consideration at compiling the present catalog. Before 1962 the catalog provides surface waves data. From 1963 NEIC, USGS began to determine magnitudes systematically by volume waves, and since that time the catalog includes the data on surface Ms and volume mb waves. To characterize solar activity we used the data on the Wolf numbers, obtained on the sites [http://sidc.oma.be/sunspot-data/] and [http://www.wdcb.ru/stp/data/solar.act/sunspot/].

On the basis of these data we revealed centennial cycles of solar activity and the Earth's seismicity, which are about 100 years long. At the beginning of each cycle in 18th, 19th and 20th centuries the seismic activity was maximal, while the Wolf numbers characterizing solar activity were minimal. Thus, there was an obvious negative correlation between the seismicity of the Earth and solar activity. In other words, the most intensive seismic and volcanic activity was observed during insignificant solar activity and vice versa.

Thus, the data for three centuries has shown an undulated change if global seismicity and solar activity with an about 100 years long cycle.

Given the presence of the most complete and reliable data for the period 1876–2012, the present work considers the centennial variations of terrestrial seismic activity in more detail. An example will be the 20th century cycle (Figure 1). For this purpose the earlier compiled catalog was prolonged till 2013. As is seen, seismicity grew rapidly in the late 19th century. In Figure 1b a minimal value of seismic energy before its increase is marked by triangle T1. It reached its maximal value at the beginning of the 20th century, then it gradually decreased (see Figure 1b and Figure 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 (Figure 1b – moment T2).

Solar activity in periods of maximal seismic energy release (in the early 20th century) had the lowest values during the whole 20th century (see Figure 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.

It had been shown earlier [*Shestopalov and Kharin*, 2006] that the 100-year cycle of solar and seismic activity is subdivided into three periods (approximately of 33 years in length), each of them is approximately equal to three 11-year solar activity cycles. It was noted in [*Shestopalov and Kharin*, 2006; *Shestopalov et al.*, 2013] 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 activity 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; $M \geq 8$ events in 2006 and 2007; and the recent seismicity of 2008–2012 verify this conclusion. The $M = 8.8$ Chilean earthquake on February 27, 2010, the $M = 9$ Tohoku earthquake on March 11, 2011 and the $M = 8.6$ earthquake in Indonesia on April 11, 2012 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 2004–2012.

In fact, as has been mentioned, the centennial solar cycle is shifted in time relative to the seismic one by several years. Therefore, the new centennial solar cycle starts after the 23th solar activity cycle, i.e. in the 24rd cycle.

Analysis of temporal variations of the number of earthquakes with different magnitudes reveals the evolution of seismicity over a centennial cycle (Figure 1c–Figure 1e). It can be seen that the strongest $M \geq 8$ earthquakes occur at the beginning of the cycle. In the middle of the cycle they are predominantly replaced by earthquakes with average magnitude ($M \geq 6.8$), and by the end of the cycle relatively weak earthquakes prevail, the number of which is growing.

3. Peculiarities of Spatial-Temporal Distribution of Earthquakes

The developed database allowed us to analyze the north–south distribution of earthquakes with different magnitudes. It can be seen from Figure 2a that the maximal number of all earthquakes for the period 1891–2012 was observed in the Southern Hemisphere at latitudes 0–10°, which apparently corresponds to the most seismically active Indonesian segment of the Pacific belt. The second, less significant maximum of seismic activity is in the Northern Hemisphere at latitudes about 30–40°, corresponding to the Alpine-Himalayan belt.

Let us analyze the changes of north-south distribution of earthquakes throughout three 33-year periods of a centennial solar activity cycle.

At the initial period of the last century (1891–1933) the maximal number of earthquakes occurred at latitudes around $30-40°$ (Figure 2b), during the second period (1934–1964) – in the Southern Hemisphere at latitudes 0–10°. The maximal number of strong earthquakes with $M \geq 7.6$ over this period in the Northern Hemisphere was almost equal to those in the Southern Hemisphere (Figure 2c).

Figure 2d shows that during the last period of the centennial cycle (1964–1996) the earthquake maximum has shifted to the Southern Hemisphere at latitudes 0–10°. Thus, our statistical analysis established the migration (inversion) of earthquake maxima in the 20th century on Earth from the Northern to Southern Hemisphere.

North–south distribution of global seismicity was also presented in the works [*Levin and Chirkov*, 1999; *Levin et al.*, 2013]. These works deal with the influence of the Earth's rotation on latitudinal distribution of earthquakes with small magnitudes. The present work describes the relationship between latitudinal distribution of strong earthquakes and solar activity over a long-term period throughout a centennial cycle. In particular, it has established that solar activity changed simultaneously with the character of latitudinal distribution of earthquakes.

The question of targeted migration of epicenters of strong earthquakes was discussed in different publications [*Nersesov et al.*, 1990; *Nevsky et al.*, 1991; *Nikolaev, Vereschagin*, 1991; *Sobolev*, 1993].

Direction of migrations varies: from east to west at a speed of 80 km/year (the North Anatolian Fault in Turkey); from south to north – 95 km/year (South America); in Central California near the San Andreas Fault Rupture the speed of migration was 3.5 km/year etc. To explain a phenomenon of targeted migration of epicenters of strong earthquakes we suggested a hypothesis of a possible sequential provoking of these earthquakes by a certain deformation front, spreading in various directions in the Earth's crust. Thus, the study indicates at a possibility of wave deformation processes in the Earth's crust, propagating at velocities of 10–100 km/year.

There are sufficient data to reach a conclusion that oscillatory structure is one of the main properties of geophysical fields [*Nersesov et al.*, 1990]. One can expect that this prop-

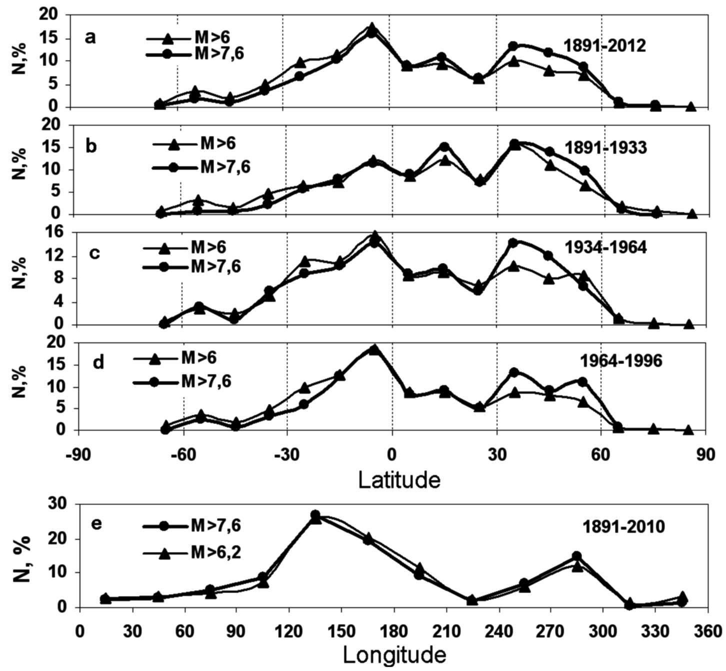

Figure 2. Latitudinal distribution of $M \geq 6$ and $M \geq 7.6$ earthquakes with a step size of 100 in a centennial cycle for the period 1891–2012: a – as a whole; b – for the initial period (1891–1933); c – for the average period (1934–1964); d – for the concluding period of a centennial cycle (1964–1996); e – longitudinal distribution of earthquakes with a step size of 300 in a centennial cycle for the above-mentioned period. The ordinate scale is expressed in percentages from the general number of earthquakes for the above-mentioned period.

erty is general for processes that take place in the Earth's interior.

We also analyzed the east-west distribution of earthquakes (Figure 2e) for the period 1891–2012. It can be seen that all these curves have two common maximums. The first one, the biggest, is located at 120–150° east longitude, the second, a less intensive maximum, can be found at $60 - 90°$ west longitude. This longitudinal distribution of earthquakes at separate periods of the centennial cycle remains almost unchangeable.

It is obvious that at intersection of north–south and east–west maxima of seismicity and volcanism, that took place during the whole centennial cycle, there is an absolute seismicity maximum, which is, in case, a manifestation of the highest endogenous activity of the Earth in the 20th century. This maximum is located in the Indonesian part of the Pacific belt, to the south of the Philippine Sea, at the junction of the southern part of the Philippine Plate with the western part of the Caroline Plate and the northern part of the Australian Plate. Generally speaking, it is a zone of conjunction of the Pacific Ocean with Eurasia and Australia.

4. Neutrons of Terrestrial Origin

A series of experimental observations in recent years has shown that seismic activity can lead to the formation of neutrons [*Kuzhevskii et al.*, 1993; *Shestopalov and Kharin*, 2006; *Shestopalov et al.*, 2013; *Sobolev et al.*, 1998]. 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. 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 a Japanese scientist, 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 [*Yasunaga*, 1993]. 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 et al.*, 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.

The present work continues this research.

4.1. Method of Research

Experiments that were simultaneously carried out in 2009–2012 in Moscow and Kamchatka have verified the recording of earthquake-related neutrons on the Earth's surface [*Shestopalov et al.*, 2011a, 2011b].

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), Moscow.

- The installation for recording thermal neutrons consists of 15 gas discharge counters of the SI-19 N 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 63 × 63GD consists of a scintillation detector constructed on the basis of crystalline scintillator NaJ(Tl) of 63×63 mm^3 in size.

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

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.

The following strong earthquakes occurred in 2010–2012:

- The $Mw = 8.8$ earthquake on February 27, 2010 near the coast of Chile, 90 km of the city of Conception at a depth of 35 km (the coordinates of the earthquake were: $\varphi = 35.909°$S, $\lambda = 72.733°$W) [http://earthquake.usgs.gov/earthquakes/eqarchives/]. Underground aftershocks occurred in February–March after this earthquake in Chile. Some earthquakes have reached magnitude $M = 7.8$.
- The $Mw = 9.0$ earthquake on March 11, 2011 near the east coast of Honshu, Japan (the coordinates of the earthquake were: $\varphi = 38.322°$N, $\lambda = 142,369°$E). The hypocenter of the most destructive aftershock was located at a depth of 32 km below sea level in the Pacific Ocean. The earthquake occurred at a distance of 70 km from a nearest area of the Japanese coastline [http://earthquake.usgs.gov/earthquakes/eqarchives/].
- The $Mw = 8.6$ earthquake on April 11, 2012 in Indonesia off the west coast of Northern Sumatra. The earthquake epicenter was located 435 km to the south–west of the city of Banda Aceh. Its hypocenter was situated in the Pacific Ocean at a depth of 23 km. A strong aftershock occurred 125 minutes after the earthquake 615 km south-west of Banda Aceh at a depth of 16 km [http://earthquake.usgs.gov/earthquakes/eqarchives/].

4.2. Results of Observations of Neutron Fluxes and Gamma Radiation with Respect to the $Mw = 8.8$ Strong Chilean Earthquake on February 27, 2010

Below we focus on the analysis of variations in neutron fluxes and gamma radiation on February 24–28, 2010 with respect to the strong $Mw = 8.8$ earthquake on February 27, 2010 at 0634 UT near the coast of Chile.

Figure 3 presents values of the K_p 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 Moscow, the intensity of thermal neutron fluxes recorded 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 $I = (Ni - N_{ph})/N_{ph} \times 100\%$, where Ni is the minute values of particle fluxes and N_{ph} is the background value of the particle flux observed on February 24.

It is seen in Figure 3 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 (Figure 3d–Figure 3f). Here the minute values of their fluxes are given in Figure 3. 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 Figure 3 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 100,000%) six hours before the earthquake; i.e., intensity grew from a minimal to a maximal value by several orders of magnitude (see Figure 3). Then, after the peak value, the intensity of particles dropped rapidly, reaching background values when the earthquake was occurring.

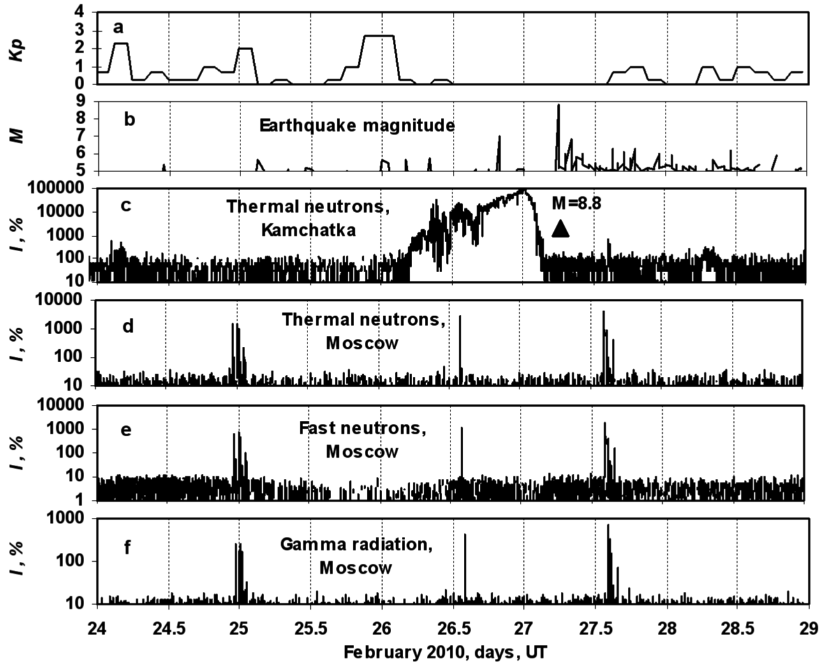

Figure 3. Temporal variations on February 24–29: a – Kp index; b – earthquake magnitude (M), c – thermal neutron flux intensity, recorded at the station in Kamchatka, d–f – thermal and fast neutron and gamma radiation flux intensity, recorded in Moscow.

4.3. Results of Observations of Neutron Fluxes and Gamma Radiation With Respect to the Strong Earthquake in Japan

The $M = 9$ earthquake in Japan on March 11, 2011 continued the list of the strongest events which were predicted to occur in the first half of the new centennial cycle. The earthquake has caused a strong tsunami, which caused extensive destruction and massive casualties on the northern islands of the Japanese archipelago. The tsunami has spread over the whole Pacific Ocean, in many coastal countries, along the whole Pacific coast of North and South America from Alaska to Chile. The earthquake and accompanying phenomena have led to accidents at the nuclear power plants in Japan.

The Japan earthquake by its magnitude and by the character of its impact on nature and people can be compared with the $M = 9$ earthquake in Indonesia on December 26, 2044 near the coast of northern Sumatra. It has also caused a tsunami with wave heights exceeding 15 m and led to extensive casualties and damage. Therefore, the forecast of such events is extremely important for all humanity. Let us show that neutron fluxes that are associated with such disasters are an important tool for studying the processes inside the Earth, and for the prediction of natural disasters.

Let us show that in case of strong events significant bursts in the intensity of neutron fluxes and gamma radiation can be observed several months prior to event. It is seen in Figure 4 that intensive bursts of neutron fluxes and gamma radiation were registered in Moscow in August 2010. Based on the minute data, the maximal amplitude of thermal neutrons in August was about 800%, that of fast neutrons, about 400%, that of gamma radiation, about 200%. In subsequent months the number of bursts and their amplitude increased. It is seen in Figure 4d that daily average variations of intensity of thermal neutron fluxes gradually grew from month to month. The maximal value of neutron fluxes was observed in December 2010 and January 2011. In December 2010, based on the minute data, the maximal amplitude of thermal neutrons was about 4000%, that of fast neutrons, about 3000%, that of gamma radiation, about 900%. The most intensive bursts occurred in February 2011. By the moment of the earthquake on March 11 the intensity of particles has reached background values.

Let us compare the character of variations in the intensity of thermal neutrons, registered in Kamchatka and in Moscow. The data for Kamchatka are presented for the period December 2010–March 2011.

It is seen in Figure 4 that, according to the data, registered in Moscow, the most intensive fluxes of thermal neutrons occurred in February 2011 (see Figure 4d–Figure 4f). Based on the minute data, the maximal amplitude during that period reached $\sim 3000\%$ for thermal neutrons, $\sim 2500\%$ for fast neutrons, 700% for gamma radiation. The characters of variations in the intensity of thermal neutrons are different for Moscow and Kamchatka. The maximal value of neutrons' intensity was observed in Kamchatka in January 2011, at that it reached its peak value of about 110,000% (see Figure 4c), i.e. the intensity of neutrons exceed the background values by three orders (a background value was several tens of percentage). Growth in neutron fluxes was

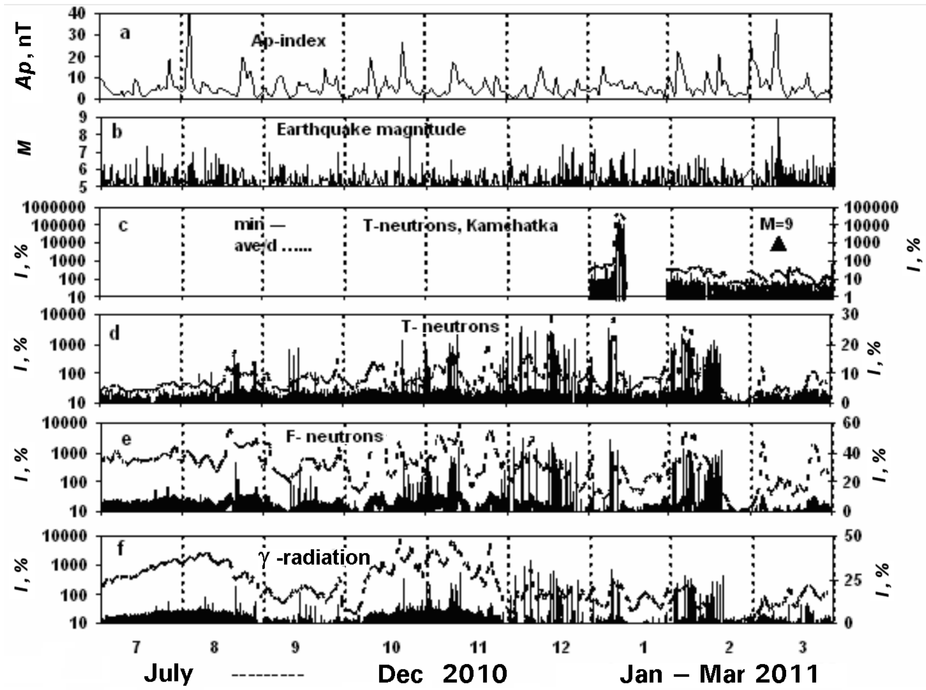

Figure 4. Temporal variations in July 2010–March 2011: a – *Ap* index; b – earthquake magnitude (M); c – thermal neutron flux intensity, recorded at the station in Kamchatka (January–March 2011); d–f – thermal and fast neutron and gamma radiation flux intensity, recorded at IZMIRAN, Moscow. The data on neutrons and gamma rays are in minutes (solid line, left-hand side scale) and in average daily values (dashed line, right-hand side scale).

not recorded in February and March. It is sees in Figure 4 that the situation in the magnetosphere in January–March 2012 was quiet. The maximal value of the *Ap* index did not exceed 40 nT.

4.4. Results of Observations of Neutron Fluxes and Gamma Radiation in Relationship With the Earthquake in Indonesia

Initial precursors of the earthquake on April 11, 2012 were recorded in November 2011 in Moscow. In this period intensive bursts of neutron fluxes were observed: thermal and fast neutrons and gamma radiation. Then, up to March 2012, bursts of neutron fluxes and gamma radiation weren't that frequent, but their intensity remained high. The most intensive bursts of particles were observed in March and in the first half of April 2012. Figure 5 presents the minute and daily values of their fluxes. It is seen in the figure that approximately three weeks prior the earthquake on April 11, 2012 the growth of intensity of thermal and fast neutrons, and gamma radiation was recorded in Moscow (see Figure 5c–Figure 5e). Based on the minute data, the maximal amplitude during this period has reached $\sim 20,000-30,000\%$ for thermal neutrons, $\sim 2000\%$ for fast neutrons, $\sim 700\%$ for gamma radiation. It is seen in the figure that separate bursts of particles were observed not only prior the earthquake, but after it. Figure 5 presents the values of the *Ap* index, which characterizes magnetic activity on global scale. It is seen in Figure 5 that geomagnetic situation in March–April 2012 was calm. The maximal value of the *Ap* index did not exceed 50 nT.

Thus we can draw the conclusion that about several months before the described events the significant bursts of neutron fluxes were observed not only in the epicenter but in areas far from the disaster area. Based on the minute data, the amplitude of these bursts was from several tens to hundreds of thousands of percentage.

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 Sumatran (December 28, 2004), Chilean (February 27, 2010) and Japanese (March 11, 2011) ones, caused a change in the duration of the day and the orientation of the Earth's revolution axis [http://www.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

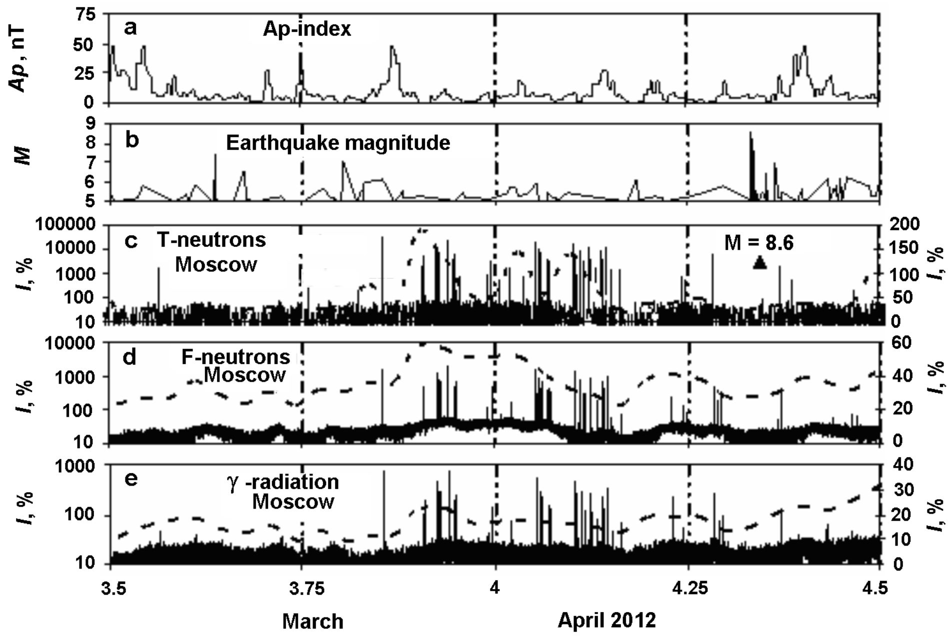

Figure 5. Temporal variations in March–April 2012: a – *Ap* index; b – earthquake magnitude (M); c–e – thermal and fast neutron and gamma radiation flux intensity, recorded at IZMIRAN, Moscow. The data on neutrons and gamma rays are in minutes (solid line, left-hand side scale) and in average daily values (dashed line, right-hand side scale).

reflect the drift of the core and its induced vibrations with a broad spectrum of frequencies relative to the viscoelastic mantle [*Barkin*, 2008; *Podobed and Nesterov*, 1982].

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 $\sim 0.2^\circ$ 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 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 [*Enikolopov et al.*, 1986; *Sharov*, 1990]. Thus, under a mechanical effect implemented in a plastic domain, the transition of rock material into an activated-onized 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. Investigations of the isotopic composition of helium from diamond deposits of metamorphic complexes in Northern Kazakhstan, which were formed due to paleoearthquakes, confirm this conclusion [*Blyuman*, 2003; *Shukolyukov et al.*, 1996]. The results of research indicate anomalously high for diamonds concentration of helium isotopes ^{3}He relative to ^{4}He. Thus, earthquakes may create favorable conditions for nuclear reactions, including the presence of deuterium and ^{3}He [*Perez et al.*, 1996].

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. 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), i.e., the medium is not continuous but hierarchically discrete [*Sadovskii et al.*, 1987]. 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 and forms a deformation front. 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. In this case hypothetical particles (Y) should be generated, capable to penetrate the geophysical medium and generate neutrons and other particles, promoting their transfer, motion and appearance at the Earth's surface.

An increase in fluxes of these particles prior to earthquakes 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 activity can be assessed on a planetary scale and the area of a disaster may be specified if a sufficient number of instruments is available.

The large-scale disaster at the Fukushima Nuclear Power Plant may need a more detailed analysis of its causes. It has been assumed that various factors of the external environment can influence the operation of a nuclear power plant, in particular neutron fluxes, which are generated during earthquakes. A possible influence of neutrons on the operation of a nuclear power plant was noted in the works [*Rogozhin and Shestopalov*, 2006, 2007].

The danger of nuclear objects in regard to earthquakes is determined by the following factors:

1. A possible damage of a nuclear reactor resulting from an earthquake.
2. An influence of neutron fluxes on its work, generated by the Earth's endogenous activity. During a very short period of time (a few seconds) the fluxes can increase by several orders.
3. An influence of particles, whose nature is presently unknown. They can appear relative to changes in the stress-strain state of the geomedium, capable to penetrate it and generate neutrons.

It is suggested that disturbances in the work of nuclear power plants in Japan, connected to the earthquake on March 11, 2011 have already started in December 2010–January 2011, when the surpass of particle fluxes over the background level was recorded in Kamchatka and has reached 100,000%. Therefore it seems desirable to organize seismic monitoring in the vicinity of nuclear power plants. For this purpose instruments recording neutron radiation as a precursor of earthquakes' prediction can be used.

6. Conclusions

1. Centennial cycles of the Earth's seismic activity were revealed; the cycles are subdivided into three periods of ~ 33 (30–40) years and related to solar activity.
2. A significant negative correlation between the Earth's seismic energy and solar activity has been found.
3. The previous 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. Intensive seismic activity and relatively low solar activity are to be observed at its beginning.
4. The earthquakes in Chile, Japan, Indonesia in 2010–2012 have continued the list of strong events which are to occur at the beginning of the new centennial cycle, which our planet has recently entered. The latest data confirm the growth of the Earth's seismic activity. In this sense, the catastrophic earthquake in Japan supports this suggestion.
5. Spatial-temporal mechanism of seismicity was established: during a centennial cycle the largest number of earthquakes have a tendency to occur along a meridional band of 120–150°E. At the beginning of a centennial cycle a maximum of seismicity is located in northern latitudes, in a concluding period of a cycle this maximum shifts to southern latitudes.
6. Ground measurements of: a) fluxes of fast and thermal neutrons as well as gamma-radiation, carried out in IZMIRAN (Moscow); b) fluxes of thermal neutrons at the Karymshina Complex Geophysical Observatory in Kamchatka in 2010–2012 have detected the particle fluxes and gamma-radiation related to the $M = 8.8$ Chilean earthquake of February 27, 2010, the $M = 9$ Tohoku earthquake on March 11, 2011 and the $M = 8.6$ earthquake in Indonesia on April 11, 2012. Both a continuous monotonic increase of particle fluxes and separate short-time increases were observed. Based on the minute data, the amplitude of this increases reached several thousands, tens and hundred thousands of percentage points. The growth of particles was observed several months prior the events.
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 earthquake epicenter may be related to neutron transmission by elements of the active hierarchically partitioned geomedium of a wave nature.
8. It has been assumed that various factors of the external environment can influence the operation of a nuclear power plant, in particular neutron fluxes, which are generated during earthquakes.

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