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A possible mechanism of stimulation of seismic activity by ionizing radiation of solar flares*

Valery M. Sorokin[1] Alexey K. Yashchenko[1] Victor A. Novikov[2,✉]

[1] *Pushkov Institute of Terrestrial Magnetism and Radio Wave Propagation of Russian Academy of Sciences*, *Troitsk*, *Moscow* 108840, *Russia*
[2] *Joint Institute for High Temperatures of Russian Academy of Sciences*, *Moscow* 125412, *Russia*

Abstract A possible mechanism of earthquake triggering by ionizing radiation of solar flares is considered. A theoretical model and results of numerical calculations of disturbance of electric field, electric current, and heat release in lithosphere associated with variation of ionosphere conductivity caused by absorption of ionizing radiation of solar flares are presented. A generation of geomagnetic field disturbances in a range of seconds/tens of seconds is possible as a result of large-scale perturbation of a conductivity of the bottom part of ionosphere in horizontal direction in the presence of external electric field. Amplitude-time characteristics of the geomagnetic disturbance depend upon a perturbation of integral conductivity of ionosphere. Depending on relation between integral Hall and Pedersen conductivities of disturbed ionosphere the oscillating and aperiodic modes of magnetic disturbances may be observed. For strong perturbations of the ionosphere conductivities amplitude of pulsations may obtain ~10^2 nT. In this case the amplitude of horizontal component of electric field on the Earth surface obtains 0.01 mV/m, electric current density in lithosphere –10^{-6} A/m^2, and the power density of heat release produced by the generated current is 10^{-7} W/m^3. It is shown that the absorption of ionizing radiation of solar flares can result in variations of a density of telluric currents in seismogenic faults comparable with a current density generated in the Earth crust by artificial pulsed power systems (geophysical MHD generator "Pamir-2" and electric pulsed facility "ERGU-600"), which provide regional earthquake triggering and spatiotemporal variation of seismic activity. Therefore, triggering of seismic events is possible not only by man-made pulsed power sources but also by the solar flares. The obtained results may be a physical basis for a novel approach to solve the problem of short-term earthquake prediction based on electromagnetic triggering phenomena.

Keywords: solar flare; ionosphere; telluric current; earthquake triggering

1 Introduction

Studies of a possible influence of solar activity on the seismic activity of the Earth have been conducted for more than a hundred years. Even in the 19th century Wolf (1853) pointed out that sunspots may exert some influence on the occurrence of earthquakes. At the present time the studies in this area are directed to find correlations between the Earth seismicity and solar activity (Wolf numbers) (Gribbin, 1971; Takayama and Suzuki, 1990; Zhang, 1998). According to Sytinsky's researches (Sytinsky, 1973; 1989; Sytinsky and Oborin, 1997), there is a certain dependence of seismicity on the 11-year solar cycle, which was verified by prediction of global seismicity and seismic activity of specific regions. A positive correlation was observed between the number of earthquakes and the phases of the 11-year solar cycle. Along with these studies there are also inverse statements that the 11-year seismic cycles have a significant negative correlation with solar activity cycles and geomagnetic disturbances (Sobolev et al., 1998). It should be noted that practically all mentioned conclusions are based on statistical analyses only. Even for the cases when the statistical analysis provides statistically significant result, the authors come to nothing more than only supposition on a mechanism of action of solar flares, or restrict to simple general discussion of this action without details (Georgieva et al., 2002). Moreover, there is a certain skepticism on a real existence of solar-terrestrial relationships resulted in statistically significant variation of seismicity (e.g., Love and Thomas, 2013). Nevertheless, new results obtained

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✉ **Corresponding author. e-mail**: novikov@ihed.ras.ru

recently (Ruzhin and Novikov, 2018) stimulate the studies of possible mechanism of such interaction. At present some hypotheses where proposed on an influence of solar activity on the Earth rotational speed (Simpson, 1968) or to activity of hurricanes (Sytinsky, 1987) that, in turn, may provoke a variation of the crust stress-strain state and earthquake triggering (Yaroshevich, 2011; Sasorova and Levin, 2017). However, the analysis made in Sobolev et al. (2012) for regions of Kamchatka, Japan, and Philippines demonstrated that amplitudes of seismic vibrations generated by typhoons, which may be considered as a possible trigger of earthquakes, does not exceed the vibrations from numerous local earthquakes of moderate magnitude of 4–5 and more strong remote earthquakes occurring in the west of the Pacific ocean. Thus, it was shown that the cyclones on the whole do not exert significant triggering impact on seismicity during several days or weeks.

We consider a possible mechanism of earthquake triggering by ionizing radiation of solar flares. This research is based on hypotheses proposed in the recently published papers on a triggering impact of sharp variations of geomagnetic field on seismicity (Sobolev et al., 2001; Zakrzhevskaya and Sobolev, 2002; Tarasov and Tarasova 2004), as well as diurnal Sq-variations (Duma and Ruzhin, 2003; Tzanis, 2010). However, the model of generation of telluric currents in the Earth crust with heterogeneous conductivity provided by solar flares is absent today. The paper presents the theoretical model and results of numerical computations of disturbance of electric field, electric current, and heat release in lithosphere due to variations of conductivity of ionosphere resulted from absorption of ionizing radiation of solar flares.

2 Disturbance of electric field by variation of ionosphere conductivity.

Solar flares are accompanied by disturbances of geomagnetic field in different ranges of periods. It may be assumed that the greatest current amplitudes in the lithosphere are induced by short-period oscillations of geomagnetic field. Below we consider characteristics of electrodynamic impact of such oscillations on the lithosphere. One of the mechanisms of generation of geomagnetic pulsations is related to a local change of ionospheric conductivity in the presence of an external electric field. Such a mechanism is considered in Bell (1976) and Lyatskiy (1978) as applied to the problems of generation of Pi2 pulsations, as well as artificial oscillations of the geomagnetic field line. These studies considered processes with characteristic periods over 10 s. The Earth-ionosphere resonator generates oscillations of geomagnetic field with periods of 1 to 100 seconds in the process of ionosphere ionization by radiation of a solar flare with a short front of its amplitude rise. For studying the characteristics of induced electric current in the lithosphere, it is necessary to modify the model to take into account the real conductivity of lithosphere. The easiest way to estimate the characteristics is an assumption of vertical geomagnetic field. The horizontal scale of the conductive region disturbed by the solar flare is of the order of the Earth's radius, and the vertical scale is of the order of the ionosphere thickness. Therefore, horizontal derivatives in the equations may be neglected. It corresponds to the fact that during the characteristic period of the field change the ionospheric currents and fields diffuse in the horizontal direction over a distance much smaller than the horizontal scale. We introduce a Cartesian coordinate system with the z axis directed vertically up along the geomagnetic field $\boldsymbol{B}$ and the x and y axes directed, respectively, along the meridian to the south and along the latitude to the east. Conductivity of ionosphere is concentrated in a layer of about 20 km maximum of which is located at an altitude of about 120 km. The thickness of conductive layer is much less than characteristic vertical scale of electric field. We assume that maximum of conductive layer is located at an altitude $z = z_1$. An external electric field $\boldsymbol{E}_{\text{ext}}$ in the ionosphere is directed parallel to the Earth's surface. A change in the ionosphere conductivity will result in disturbance of ionospheric currents and, accordingly, in generation of disturbance of magnetic and electric fields. In the conductive ionosphere the electric field disturbance $\boldsymbol{E}$ satisfies the equation (Bladel, 2007):

$$\nabla\times\nabla\times\boldsymbol{E}+\mu_0\frac{\partial}{\partial t}\hat{\sigma}(\boldsymbol{r},t)(\boldsymbol{E}+\boldsymbol{E}_{\text{ext}})=0, \tag{1}$$

where $\hat{\sigma}(\boldsymbol{r},t)$ is tensor of disturbed conductivity of ionospheric plasma. Above conducting ionosphere layer the electric field disturbance satisfies the equation (Kelley, 2009):

$$(\nabla\times\nabla\times\boldsymbol{E})_{\perp}+\frac{1}{u^2}\frac{\partial^2\boldsymbol{E}_{\perp}}{\partial t^2}=0 \tag{2}$$

where u is Alfven velocity, symbol $\perp$ means transverse components of the vector relative to the vertical. We assume that the conductivity of the Earth-ionosphere layer is zero and, therefore, the electric field is determined from the Laplace's equation:

$$\Delta\boldsymbol{E}=0 \tag{3}$$

Integrating equations (1) over the thickness of the conducting ionosphere layer, we obtain the boundary conditions on this layer for the tangent components of disturbance of horizontal components $\boldsymbol{E}=\left(E_x,E_y\right)$ of electric field:

$$\left\{\frac{\partial \boldsymbol{E}}{\partial z}\right\}-\mu_0\frac{\partial}{\partial t}\left(\hat{\Sigma}\boldsymbol{E}\right)=\mu_0\frac{\mathrm{d}\hat{\Sigma}}{\mathrm{d}t}\boldsymbol{E}_{\mathrm{ext}};\quad \{\boldsymbol{E}\}=0, \tag{4}$$

where curly brackets {...} denote a jump of corresponding value when passing through a conducting level, $\hat{\Sigma}$ is time-dependent tensor of integral conductivity of ionosphere (Baker and Martyn, 1953):

$$\hat{\boldsymbol{\Sigma}}(t)=\begin{pmatrix}\Sigma_P(t) & \Sigma_H(t)\\ -\Sigma_H(t) & \Sigma_P(t)\end{pmatrix}.$$

Above the conductive ionosphere layer the electric field is determined by equation (2). Its solution has the form of an outgoing magneto-acoustic wave

$$\boldsymbol{E}(z,t)=\boldsymbol{f}\left(t-\frac{z}{u}\right), \tag{5}$$

The Earth-ionosphere layer is non-conductive. Hence, for a quasi-stationary approximation, the electric field disturbance in this layer is determined from the equation:

$$\frac{\partial^2\boldsymbol{E}}{\partial z^2}=0;\quad 0<z<z_1,$$

the general solution of which is

$$\boldsymbol{E}(z,t)=\boldsymbol{E}_0(t)+\boldsymbol{E}_1(t)\frac{z}{z_1}. \tag{6}$$

$\boldsymbol{E}_0$ in equation (6) is electric field on the lithosphere surface. Substituting solutions (5) and (6) into the boundary condition (4), we obtain the equation for the electric field in the conductive ionosphere layer:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\hat{\Sigma}_{\mathrm{e}}\left(\boldsymbol{E}_0+\boldsymbol{E}_1\right)\right]+\frac{1}{\mu_0z_1}\boldsymbol{E}_1=-\frac{\mathrm{d}\hat{\Sigma}_{\mathrm{e}}}{\mathrm{d}t}\boldsymbol{E}_{\mathrm{ext}} \tag{7}$$

where a tensor of efficient integral conductivity is

$$\hat{\boldsymbol{\Sigma}}_{\mathrm{e}}(t)=\begin{pmatrix}\Sigma_P(t)+1/\mu_0u & \Sigma_H(t)\\ -\Sigma_H(t) & \Sigma_P(t)+1/\mu_0u\end{pmatrix} \tag{8}$$

For an approximation of an ideally conducting lithosphere the tangent component of the electric field disturbance on the lithosphere surface is $\boldsymbol{E}_0=0$. In this case the equation (7) will be transformed into an ordinary differential equation for determination of $\boldsymbol{E}_1(t)$. For the case of lithosphere with finite conductivity for determination of $\boldsymbol{E}_1(t)$ it is necessary to exclude in this equation an unknown function $\boldsymbol{E}_0(t)$.

3 Characteristics of electric filed and current in lithosphere.

Denote the disturbance of electric field in the ionosphere as $\boldsymbol{E}_i=\boldsymbol{E}_0+\boldsymbol{E}_1$ and go to the complex values according to formulas:

$$\Sigma=\Sigma_P-i\,\Sigma_H;\quad \boldsymbol{E}=\boldsymbol{E}_x+i\,\boldsymbol{E}_y.$$

Rewrite the equation (7) as

$$\begin{aligned}&\frac{\mathrm{d}}{\mathrm{d}t}(\Sigma_{\mathrm{e}}E_i)+\frac{1}{\mu_0z_1}E_i-\frac{1}{\mu_0z_1}E_0=-\frac{\mathrm{d}\Sigma_{\mathrm{e}}}{\mathrm{d}t}E_{\mathrm{ext}};\\ &E_i=E_0+E_1.\end{aligned} \tag{9}$$

Considering the electric field in the lithosphere, we assume that the lithosphere conductivity $\sigma(z)$ depends on the vertical coordinate. The electric field is described by equation

$$\frac{\partial^2\boldsymbol{E}}{\partial z^2}-\mu_0\sigma(z)\frac{\partial\boldsymbol{E}}{\partial t}=0;\quad z<0. \tag{10}$$

At the Earth-atmosphere boundary the horizontal component of the electric field and its normal derivative are continuous, and the field decreases into the lithosphere depth:

$$\left.\left\{\frac{\partial\boldsymbol{E}}{\partial z}\right\}\right|_{z=0}=0;\quad \{\boldsymbol{E}\}|_{z=0}=0;\quad \boldsymbol{E}|_{z\to-\infty}=0. \tag{11}$$

Express the field disturbance on the Earth's surface $\boldsymbol{E}_0$ as its value at the level of ionosphere. For that we use equation (11), make the Laplace time transformation, and get the following equation:

$$\frac{\mathrm{d}^2\tilde{\boldsymbol{E}}}{\mathrm{d}z^2}=\mu_0\sigma(z)s\tilde{\boldsymbol{E}}.$$

Its solution, which satisfies the boundary condition at $z=0$, looks like

$$\tilde{\boldsymbol{E}}(z,s)=\tilde{\boldsymbol{E}}_0(s)f(z,s);\quad \tilde{\boldsymbol{E}}_0(s)=\int_0^\infty\boldsymbol{E}_0(t)\exp(-st)\,\mathrm{d}t.$$

The function $f(z,s)$ is a solution of the following boundary problem:

$$\frac{\mathrm{d}^2f}{\mathrm{d}z^2}=\mu_0\sigma(z)sf;\quad f(0,s)=1;\quad f(-\infty,s)=0. \tag{12}$$

It is evident that $f(z,s)$ is defined only by distribution of the lithosphere conductivity $\sigma(z)$. Using the boundary condition on the lithosphere surface (11), we get the following relation:

$$\tilde{\boldsymbol{E}}_0(s)=\frac{\tilde{\boldsymbol{E}}_i(s)}{1+z_1f'(0,s)};\quad f'(0,s)\equiv\left.\frac{\mathrm{d}f(z,s)}{\mathrm{d}z}\right|_{z=0}$$

Time dependence $\boldsymbol{E}_0(t)$ may be obtained from this equality by using the reverse Laplace transformation:

$$\begin{aligned}E_0(t)&=\int_0^t G(t-t')\,E_i(t')\,\mathrm{d}t';\\ G(t)&=L^{-1}\left\{\frac{1}{1+z_1f'(0,s)}\right\},\end{aligned} \tag{13}$$

where symbol $L^{-1}\{\cdots\}$ denotes the operation of the reverse Laplace transformation. Substituting (13) into (9), we obtain an integro-differential equation for $E_i\,(t)$:

$$\frac{\mathrm{d}\boldsymbol{E}_i(t)}{\mathrm{d}t}+\Omega(t)\boldsymbol{E}_i(t)-\Omega_0(t)\int_0^t G(t-t')\,E_i(t')\,\mathrm{d}t'$$
$$=-\Omega_1(t)\boldsymbol{E}_{\mathrm{ext}}, \tag{14}$$

where

$$\Omega_0(t)=\frac{1}{\mu_0 z_1 \Sigma_{\mathrm{e}}(t)};\quad \Omega_1(t)=\frac{1}{\Sigma_{\mathrm{e}}(t)}\frac{\mathrm{d}\Sigma_{\mathrm{e}}(t)}{\mathrm{d}t};$$
$$\Omega(t)=\Omega_0(t)+\Omega_1(t);\quad \boldsymbol{E}_i(0)=0.$$

In extreme case of ideally conductive lithosphere at $\sigma\to\infty$ we have $f'(0,s)\to\infty$, $G\to 0$. The kernel element $G(t-t')$ of integration of equation (14), which is defined by formulas (12) and (13), as well as the algorithm of its determination are described in the Appendix. After determination of electric field in ionosphere $E_i(t)$ using equation (14), we calculate its time dependence on lithosphere surface by the formula (13). The spatial-temporal distribution of electric field in lithosphere is found from equation (10), solving the boundary value problem:

$$\begin{aligned}&\frac{\partial^2\boldsymbol{E}}{\partial z^2}-\mu_0\sigma(z)\frac{\partial\boldsymbol{E}}{\partial t}=0;\\ &\boldsymbol{E}(z,t)|_{z=0}=\boldsymbol{E}_0(t);\\ &\boldsymbol{E}(z_m,t)=0,\\ &\boldsymbol{E}(z,0)=0;\\ &z_m<z<0.\end{aligned} \tag{15}$$

The values of electric field obtained by using the equation (15) provided a possibility of calculation of the spatial-temporal distribution of electric current density and the power density of heat release in the lithosphere by using the following formulas:

$$j(z,t)=\sigma(z)\,|\boldsymbol{E}(z,t)|;\quad q(z,t)=\sigma(z)\,|\boldsymbol{E}(z,t)|^2. \tag{16}$$

The formulas (15) and (16) allow analyzing an electrodynamic effect of solar flares on the lithosphere. We present the results of calculations of the spatial and temporal distributions of amplitudes of the electric field, current density, and power density of heat release in lithosphere, accompanying the disturbance of ionospheric conductivity under action of ionizing radiation of solar flares. For evaluation of electro-dynamic effects, we assume that under action of an ionizing radiation pulse the integral conductivities of ionosphere are changing in time according to the following formula:

$$\Sigma_{P,H}(t)=\Sigma_0\left\{1+k_{P,H}\left[1-\exp\left(-\frac{t^2}{\tau^2}\right)\right]\right\}$$

The following parameters were taken for calculations:

$$z_1=90\ \mathrm{km};u=500\ \mathrm{km}/s;$$
$$k_p=1;k_H=6;$$
$$E_{x0}=10\ \mathrm{mV/m},\ E_{y0}=0$$

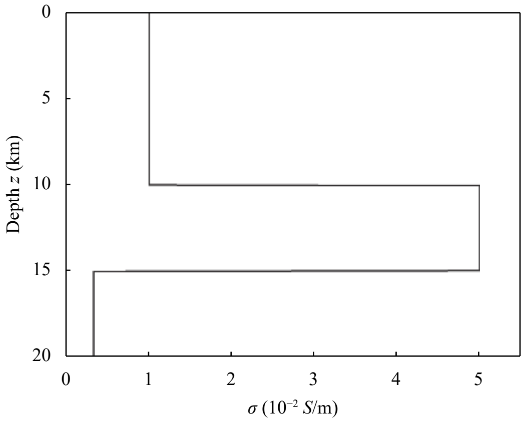

Figure 1 A depth dependence of electrical conductivity of lithosphere

The depth dependence of electrical conductivity of lithosphere is shown in Figure 1 (Fainberg et al., 2004).

Figure 2 shows the results of calculation of the time dependence of the electric field components on the lithosphere surface, the modulus of electric current density, and the power density of heat release at various depths for various characteristics of the impact on the ionosphere. The calculations showed that the current and the heat release power decrease in the lithosphere depth. However, in the layer of increased conductivity these values sharply increase.

Figure 3 shows calculation results for dependence of the modulus of electric current density on the lithosphere depth at different points in time for different characteristics of the impact on ionosphere. The calculations demonstrate that the current is concentrated in the layer with increased conductivity. The current amplitude is greater for those flares that more disturb the ionosphere conductivity.

Figure 4 shows the results of calculation of dependence of the maximum electric current density at the depth of lithosphere of z = 10 km on the characteristic rise time of the ionospheric conductivity resulting from absorption of ionizing radiation of a solar flare. It follows from the calculations that the current amplitude strongly depends on the rise time of the flash front. Fast ionization jumps result in large currents compared with a slow increase of the conductivity disturbance.

The calculations demonstrated that as a result of a jump of integral conductivities of ionosphere within ten seconds electric fields with an amplitude of the order of 0.1 to 0.01 mV/m and electric currents with density of 10^{-6} to 10^{-7} A/m^2 are induced in the lithosphere, and in this case the heat is released of power of 0.1 to 0.01 μW/m^3. The electric current is concentrated in the lithosphere within layers with high electrical conductivity. It is shown that if the layer in the lithosphere at a depth of 10 km has the conductivity five times higher in relation to surrounding layers, then the current density there increases by an order compared to its value at a smaller depth.

4 Discussion

The main question related to the earthquake triggering by impact of solar flares to lithosphere may be formulated as: "Is it possible to trigger the seismic event by electric current pulse of very low amplitude (10^{-6} to 10^{-7} A/m^2) calculated with application of the numerical model described above (see Figures 3 and 4)?" In this case we need to compare these theoretical results with field observations of response of regional seismic activity to another type of pulsed electric actions on the Earth crust like actions of solar flares with similar duration (several seconds) and

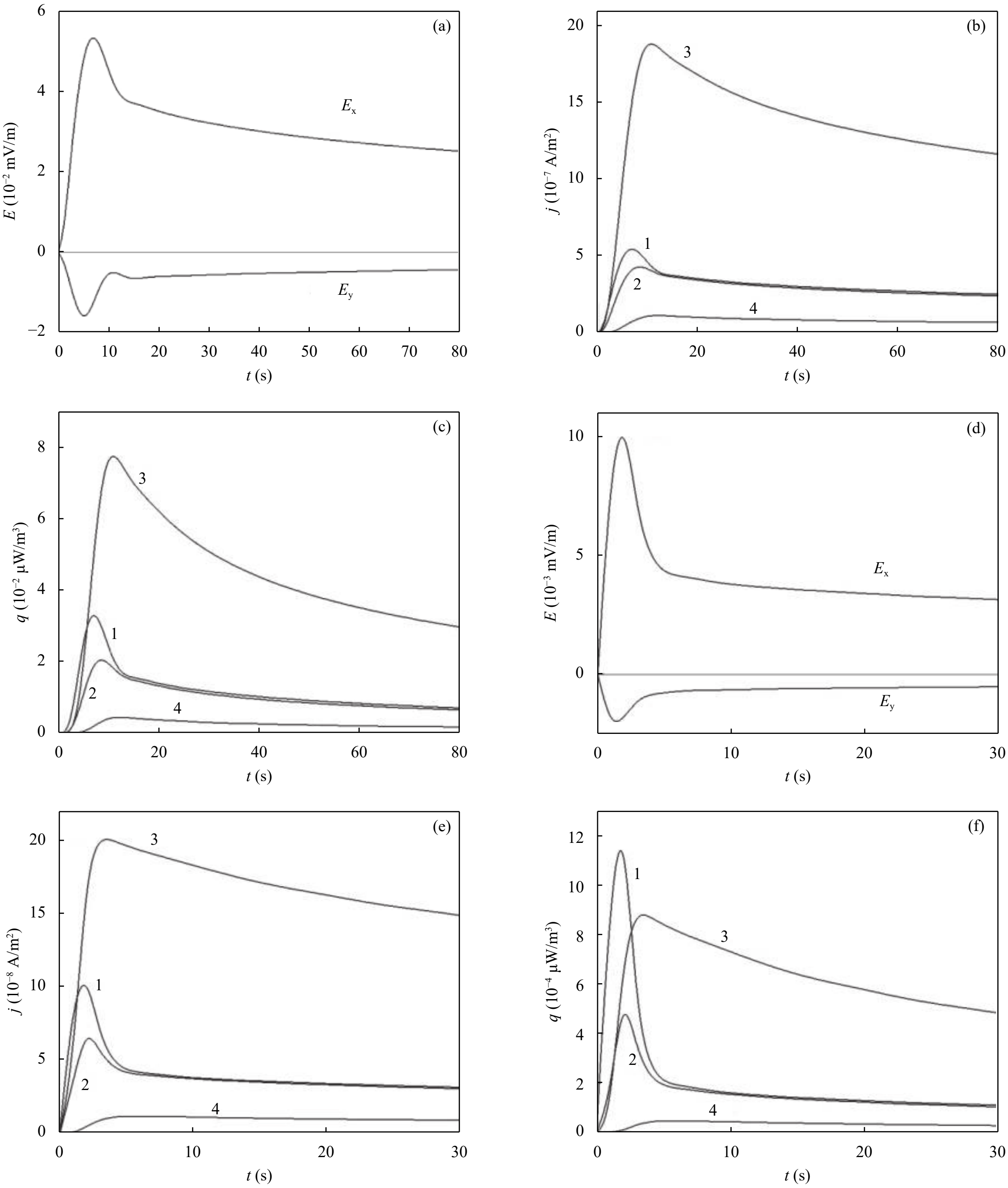

Figure 2 Time dependence of electric field components on the lithosphere surface (a, d), the modulus of electric current density (b, e), and the power density of heat release (c, f) at various depths (1:0 km; 2:5 km; 3:15 km; 4:20 km) for various characteristics of the impact on the ionosphere (for a, b, c, $\tau = 5$ s, $\Sigma_0 = 1$ S; for d, e, f, $\tau = 1$ s, $\Sigma_0 = 0.1$ S).

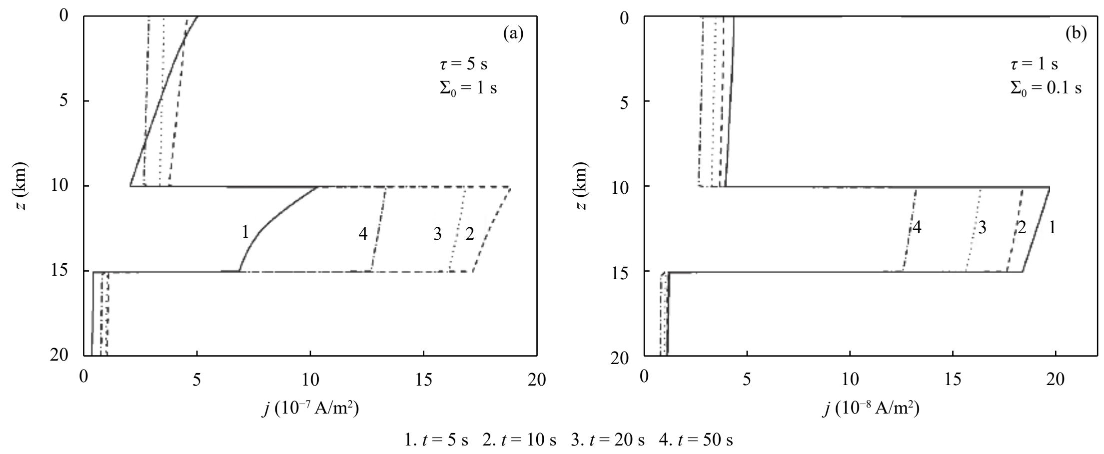

Figure 3 Dependence of the modulus of electric current density on the lithosphere depth at different points in-time for different characteristics of the impact on ionosphere (characteristic duration of the front of the ionosphere conductivity build-up τ and the conductivity value Σ_0

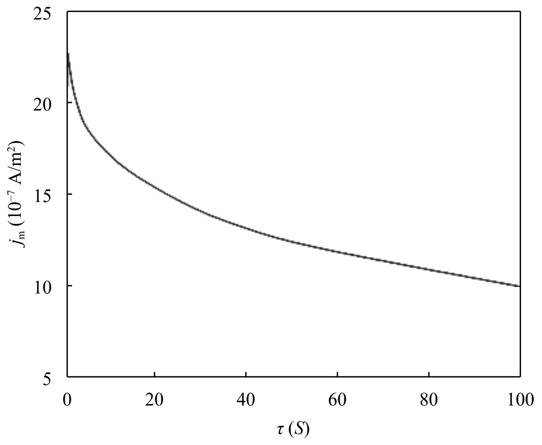

Figure 4 Dependence of the maximum electric current density at the depth of lithosphere of z = 10 km onthe characteristic time τ of the ionosphere conductivity build-up resulted from absorption of ionizing radiation of a solar flare. The following parameters were selected for calculations: $\Sigma_{P0} = \Sigma_{H0} = 1$ S, $E_{x0} = 3$ mV/m, $E_{y0} = 0$, $k_p = 1$, $k_H = 6$

generation of similar telluric currents in lithosphere. For this purpose we can use a case of man-made generation of telluric currents with application of pulsed power systems injected direct current (DC) into the Earth crust (Zeigarnik et al., 2018). At present, on the basis of field investigations and laboratory studies, the principal possibility of electromagnetic triggering of seismic events has been proved (Bogomolov et al., 2004, Novikov et al., 2017, Zeigarnik et al., 2018). An influence of powerful electromagnetic pulses of a magneto-hydrodynamic (MHD) generator on the seismic activity of the Pamirs and Northern Tian Shan (Tarasov and Tarasova, 2004; Avagimov et al., 2006) has been discovered. The MHD generator of "Pamir" type was used as a source of DC pulse for deep electromagnetic sounding of the Earth crust at the Garm (Tajikistan) and Bishkek (Kirghizia) test sites. The load of MHD generator was the grounded electric dipole with a distance between electrodes of 4.5 km and a resistance of 0.4 Ohms. During MHD generator operation the DC current in the dipole reached 0.28–2.8 kA, the pulse duration was 1.7–12.1 s, and the total energy injected to the Earth crust was 1.2–23.1 MJ. Statistical analysis of regional seismicity in both

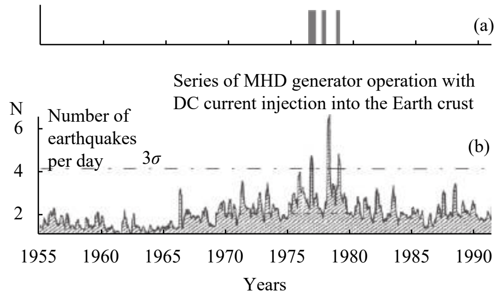

Figure 5 Daily nummber of earthquakes at Garm geophysical test site (Pamirs, Tajikistan) in the upper layer (0–5 km) of the Earth crust of Tajik depression (b) and series of MHD operations (a) for DC current injection into the Earth crust

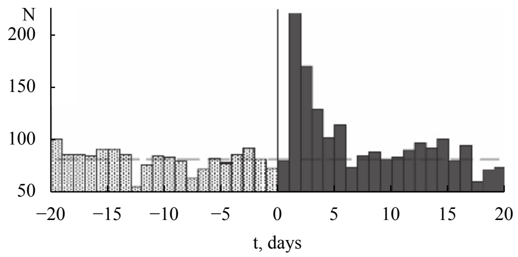

Figure 6 Daily nummber of earthquakes in the upper layer (0–5 km) of the Earth crust of Bishkek geodynamical proving ground (Northern Tianshan before (<0) and after (>0) operation of MHD generator for DC current injection into the Earth crust

regions (Pamirs and Northern Tianshan, see Figures 5 and 6) revealed that the number of earthquakes after operation of the MHD generator becomes noticeably higher than before. An increased level of seismic activity was observed for 3–6 days after operation of the MHD generator.

It was supposed that electromagnetic pulses provided by the MHD generator result in significant and prolonged change of seismic activity over the region under study and adjacent territories. During a series of experiments with the pulsed MHD generator, the relative number of weak seismic events, seismic activity of the region and earthquake clustering increase. Currently, the Bishkek geodynamic test site performs electromagnetic monitoring of the Earth crust with application of a special high-current source, an electrical generator facility (ERGU-600), which provides the pulses of DC current of 600 A in the same grounded dipole. In some modes of electric current injection into the crust the energy input is comparable to the energy of a weak earthquake (~10^8 J) and exceeds the energy input during operation of geophysical MHD generators. The results were obtained on triggering impact of electric current injection into the Earth crust on the rise of weak seismicity. The observed effect is similar to results during operation of MHD generators, but in the case of ERGU-600 application it is weaker (Zeigarnik et al., 2018). Results of statistical analysis of variation of seismic activity under man-made electromagnetic impact is verified by monitoring of geoacoustic emission in the wells of Bishkek geodynamical proving ground (Gavrilov et al., 2011; Zakupin et al., 2014), as well as miscroseismiciy (Zeigarnik et al., 2018) demonstrating the electric/electromagnetic stimulation of crack formations in the Earth crust. Moreover, results of the field experiments on electromagnetic triggered seismicity were proved by numerous laboratory experiments for a study of response of acoustic emission (crack formation) of rock samples to electromagnetic pulses with application of special press equipment (Sobolev and Ponomarev 2003; Bogomolov et al., 2004, Lapshin et al., 2016; Avagimov et al., 2006), as well as of triggering the macro-event (laboratory "earthquake") by DC current pulses with application of the spring-block model simulated a seismogenic fault (Novikov et al., 2017).

Estimations of current distribution from electric grounded dipole supplied by pulsed MHD generator "Pamir-2" or electric pulsed power system ERGU-600 for real deep geoelectric structure of the Northern Tien Shan region (Rybin, 2011) in the area of field experiments described above demonstrated that at a depth of location of regional earthquake sources (5 to 10 km) the current density is 10^{-7}–10^{-8} A/m^2 (Novikov et al., 2009). Consequently, the current density provided by man-made power source (10^{-7}–10^{-8} A/m^2) resulted in variation of regional seismicity is comparable with a density of telluric currents generated by solar flares (10^{-6}–10^{-7} A/m^2), as well as duration of DC current injection (seconds) is comparable with duration of solar flare action (seconds to minutes) that supports an idea of real existence of solar-terrestrial electromagnetic-seismic relations. Nevertheless, the mechanism of interaction of DC current of very low density with stressed rocks resulted in the earthquake triggering is not clear yet. Today there some hypotheses of electromagnetic triggering of earthquakes both by excitation of vibrations in the Earth crust (Bogomolov, 2010) and stimulation of fluid migration into the fault area under external electric actions (Novikov and Novikova, 2014) resulted in decrease of the fault strength. It should be noted that these hypotheses are phenomenological only and require detail theoretical justification and experimental verification under laboratory and field conditions.

5 Conclusions

We demonstrated by numerical calculations and subsequent comparison of their results with data of field observations that the absorption of ionizing radiation of solar flares may result in variations of telluric current densities in the seismogenic faults comparable with the current density generated in the Earth crust by artificial pulsed power sources used for active electromagnetic monitoring (MHD generators and electric pulsed power systems of ERGU-600 type). Therefore, triggering of seismic events is possible by not only artificial sources of electric current injected into the Earth crust, but also the solar flares. A generation of geomagnetic field disturbances in a range of seconds/tens of seconds is possible as a result of large-scale perturbation of a conductivity of the bottom part of ionosphere in horizontal direction in the presence of external electric field. Amplitude-time characteristics of the signal depend upon a perturbation of integral conductivity of ionosphere. Depending on relation between integral Hall and Pedersen conductivities of disturbed ionosphere the oscillating and aperiodic modes of magnetic disturbances may be observed. For strong perturbations of the ionosphere conductivities amplitude of pulsations may obtain ~10^2 nT. In this case the amplitude of horizontal component of electric field on the Earth surface obtains 0.01 mV/m, electric current density in lithosphere –10^{-6} A/m^2, and the power density of heat release produced by the generated current is 10^{-7} W/m^3. The calculations demonstrate that the current is concentrated in the layer with increased conductivity. It was shown that if the electric conductivity at a depth of 10 km is five times more than in surrounding layers, then the current density there may increase by an order in relation to the current density in the upper layer. The current amplitude in lithosphere is much greater for the flares with fast front of radiation increase in comparison with slower processes of ionization of ionosphere.

The obtained results may serve as a physical background of a new approach to the problem of short-term prediction of earthquakes based on electromagnetic triggering phenomena. This approach is formulated in (Sobolev, 2011) where it is proposed to monitor the triggering phenomena in an area of catastrophic earthquake preparation defined on a basis of the middle-term earthquake prediction (Zavyalov, 2006).

Appendix

For solving the equation (14) it is necessary to find a kernel $G(t)$, which is defined by formulas (12) and (13). We obtain the solving of boundary problem (12) by transformation of this equation into a system of first-order equations:

$$\frac{\mathrm{d}f}{\mathrm{d}z} = g; \quad \frac{\mathrm{d}g}{\mathrm{d}z} = q^2 f;$$
$$q^2(z,s) = \mu_0 \sigma(z) s$$

We define a function $R(z)$ by formula $R = g/f$ and obtain Riccati equation for it:

$$\frac{\mathrm{d}R}{\mathrm{d}z} + R^2 = q^2$$

We assume that lithosphere conductivity at $z < z_m$ is constant and equals to σ_m. As it follows from this equation the function $R(z)$ at $z < z_m$ is constant and equals to $R(z_m) = q_m = \sqrt{\mu_0 \sigma_m s}$. This equality is a boundary condition for the Riccati equation:

$$\frac{\mathrm{d}R(z,s)}{\mathrm{d}z} + R^2(z,s) = q^2(z,s)$$
$$R(z_m,s) = q_m = \sqrt{\mu_0 \sigma_m s} \quad ; \quad z_m < z < 0$$

The solving of this equation is found for each s and after that its value is determined at $z = 0$. Since according to (12), $f(0,s) = 1$, then assuming $z = 0$, we obtain:

$$R(0,s) = \frac{g(0,s)}{f(0,s)} = \left.\frac{\mathrm{d}f(z,0)}{\mathrm{d}z}\right|_{z=0} \equiv f'(0,s)$$

Therefore, the kernel of equation (14) is:

$$G(t) = L^{-1}\left\{\frac{1}{1 + z_1 R(0,s)}\right\}.$$

The Laplace reverse conversion is made with application of the algorithm described in (Stehfest, 1970).

After the kernel determination the equation (14) is solved by finite-difference method on the time interval $t = (0, t_m)$ by approximation of derivative by formula of forward difference and an integral by quadrangle formula:

$$E_i[(k+1)\Delta t] = [1 - \Omega(k\Delta t)\Delta t]\, E_i(k\Delta t) +$$
$$\Omega_0(k\Delta t)\Delta t^2 \sum_{m=0}^{k} G[(k-m)\,\Delta t]\, E_i(m\Delta t) -$$
$$\Omega_1(k\Delta t)\Delta t\; E_{ext} E_i(0) = 0; \quad k = 0 \ldots n_0; \quad n_0 = [t_m/\Delta t]$$

Because the kernel of convolution operator $G(t)$ diverges at $t \to 0$ as $1/\sqrt{t}$, then this integrable feature is excluded by representation the kernel as:

$$G(t) \to G_{\mathrm{reg}}(t) = G(t)\left[1 - \exp\left(-t^2/t_{\mathrm{reg}}^2\right)\right]$$

A value of t_{reg} is selected much less than characteristic time scales of variations of electromagnetic field $t_{\mathrm{reg}} <<$ 1 c.

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References

Avagimov AA, Zeigarnik VA and Klyuchkin VN (2006) On the structure of acoustic emission of model samples in response to an external energy action. Phys Solid Earth **42**(10): 824–829

Baker WG and Martyn DF (1953) Electric currents in the ionosphere I. The Conductivity. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **246**(913): 281–294

Bladel JGV (2007) Electromagnetic Fields. Hoboken, New Jersey: Wiley-Interscience.

Bell TF (1976) ULF wave generation through particle precipitation induced by VLF transmitters. J Geophys Res **81**(19): 3 316–3 326

Bogomolov LM (2010) Electromagnetic effect on microcrack kinetics and electro-induced variations in acoustic emission of rocks. Fiz Mezomekh **13**(3): 39–56 (in Russian)

Bogomolov LM, Il'ichev PV, Novikov VA, Okunev VI, Sychev VN and Zakupin AS (2004) Acoustic emissions response of rocks to electric power action as seismic-electric effect manifestation. Ann Geophys **47**(1): 65–72

Duma G and Ruzhin Yu (2003) Diurnal changes of earthquake activity and geomagnetic Sq variations Nat Hazards Earth Syst Sci **3**: 171–177

Fainberg EB, Vasil'eva TA, Avagimov AA and Zeigarnik VA (2004) Generation of heat flows in the Earth's interior by global geomagnetic storms. Phys Solid Earth **40**(4): 315–322

Gavrilov VA, Bogomolov LM, Zakupin AS (2011) Comparison of the geoacoustic measurements in boreholes with the data of laboratory and in-situ experiments on electromagnetic excitation of rocks. Phys Solid Earth **47**(11): 1 009–1 019

Georgieva K, Kirov B, Atanasov D (2002) On the relation between solar activity and seismicity on different time scales. J Atmos Electr **22**(3): 291–300

Gribbin J (1971) Relation of sunspot and earthquake activity Science **173**(3996): 558

Kelley MC (2009) The Earth ionosphere: Plasma physics and electrodynamics. Amsterdam, Boston, Academic Press.

Lapshin VB, Patonin AV, Ponomarev AV, Potanina MG, Smirnov VB and Stroganova SM (2016) Initiation of acoustic emission in fluid-saturated samples. Doklady Earth Sciences **469**(1): 705–709

Love JJ and Thomas JN (2013) Insignificant solar-terrestrial triggering of earthquakes Geophys Res Lett **40**: 1 165–1 170

Lyatskiy VB (1978) Current systems of magnetosphere-ionosphere perturbations. Nauka, Leningrad (in Russian)

Novikov V and Novikova E (2014) Electromagnetic stimulation of fluid migration into fault area and earthquake triggering phenomena Geophys Res Abstr **16**: EGU201-14-12790

Novikov VA, Okunev VI, Klychkin VN, Liu J, Ruzhin YuYa and Shen X (2017) Electrical triggering of earthquakes: Results of laboratory experiments at spring-block models. Earthq Sci **30**(4): 167–172

Novikov V, Zeigarnik V, Konev Yu, Rickman V (2009) Electric Triggering of Crack Formations in the Fault for Release of Tectonic Stresses Eos Trans. AGU Fall Meet. Suppl., Abstract **90**(52): S51C-1447

Ruzhin YuYa and Novikov VA (2018) The response of global seismicity to solar flares of September, 2017 Intl J Electr Appl Res **5**: 1–10

Rybin AK (2011) Deep structure and modern geodynamics of the Central Tyan-Shan according to results of magneto-telluric survey. Moscow press: Nauchniy Mir, Moscow

Sasorova EV and Levin BV (2017) On relation of variations of the Earth's rotational speed and its seismic activity. Vestnik KRAUNTS **20**(4): 91–100

Simpson IF (1968) Solar activity as a triggering mechanism for earthquakes. Earth Planet Sci Lett **3**(5): 417–425

Sobolev GA (2011) Seismicity dynamics and earthquake predictability. Nat Hazards Earth Syst Sci **11**: 445–458

Sobolev GA and Ponomarev AV (2003) Physics of Earthquakes and Precursors. Moscow, Nauka (in Russian)

Sobolev GA, Shestopalov IP, Kharin EP (1998) Implications of solar flares for seismic activity of the Earth. Physics of the Solid Earth **34**(7): 603–607

Sobolev GA, Zakrzhevskaya NA and Kharin (2001) On the coupling of seismicity with magnetic storms Phys Solid Earth **11**: 62–72

Sobolev GA, Zakrzhevskaya NA and Sobolev DG (2012) The effects of cyclones on seismicity. J Volcanolog Seismol **6**(2): 89–99

Stehfest H (1970) Algorithm, 368: Numerical inversion of Laplace transforms [D5]. Comm ACM **13**(1): 47–49

Sytinsky AD (1973) On an influence of solar activity on the Earth's seismicity. Doklady Academii Nauk USSR. **209**(15): 1 078–1 081

Sytinsky AD (1987) Connection of the Earth Seismicity with Solar Activity and Atmospheric Processes. Gidrometeoizdat, Leningrad (in Russian)

Sytinsky AD (1989) On relation of earthquakes and solar activity Doklady Earth Sciences. **2**: 13–30

Sytinsky AD and Oborin DA (1997) Action of perturbations of interplanetary medium on Earth's seismicity and atmosphere. Geomag Aeron **37**(2): 138–141

Takayama T and Suzuki T (1990) On the relation between the sunspot number and the destructive earthquakes in Japan. Bull Earthq Resh Inst Tokyo Imperial University **8**(3): 373–374

Tarasov NT and Tarasova NV (2004) Spatial-temporal structure of seismicity of the North Tien Shan and its change under effect of high energy electromagnetic pulses. Ann Geophys **47**(1): 199–212

Tzanis A (2010) An examination of the possibility of earthquake triggering by the ionosphere-lithosphere electro-mechanical coupling. Hellen J Geosci **45**(1): 307–316

Wolf R (1853) On the periodic return of the minimum of sun-spots: The agreement between those periods and the variations of magnetic declination Philos. Magazine **5**: 67

Yaroshevich MI (2011) Tropical cyclones as a possible factor affecting seismic activity in the cyclonic zone of the northwestern Pacific. Izvestiya, Physics of the Solid Earth **47**(7): 636–640

Zakrzhevskaya NA and Sobolev GA (2002) On the seismicity effect of magnetic storms. Phys Solid Earth **38**(4): 249–261

Zakupin AS, Mubassarova VA, Il'ichev PV and Bogomolov LM (2014) Seismoacoustic responces to high-power electric pulses from well logging data at the Bishkek geodynamical test area. Phys Solid Earth **50**(5): 692–706

Zavyalov AD (2006) Medium-term earthquake prediction: basics, methodology, implementation. Nauka, Moscow (in Russian)

Zeigarnik V, Avagimov A, Novikov V, Rybin A, Schelochkov G, Bragin V, Sychev V, Bogomolov L and Tarasov N (2018) Earthquake hazard mitigation by electromagnetic influence on seismic activity: Results of forty-year field experiment on injection of DC electrical pulses into the Earth crust Geophys Res Abstracts **20**: EGU2018-15436-1

Zhang GQ (1998) Relationship between global seismicity and solar activities. Acta Seismologica Sinica **11**(4): 495–500