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Electrodynamic Model of Atmospheric and Ionospheric Processes on the Eve of an Earthquake

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Abstract—Electric field generation and its accompanying phenomena in the atmosphere–ionosphere system have been intensively studied in recent years. This paper considers the results of these studies, which have served as the physical basis for the model of lithosphere–ionosphere coupling. According to our model, the intensive processes in the lower atmosphere and lithosphere have an electrodynamic effect on the ionospheric plasma. The model was used to conduct theoretical studies of plasma and electromagnetic effects accompanying the generation of conduction current in the global circuit. It has been shown that the electrodynamic model of the influence of seismic and meteorological processes on cosmic plasma can serve as a physical basis for a satellite system to monitor earthquake precursors and the catastrophic phase of typhoon development. The model makes it possible to couple the satellite data of electromagnetic and plasma measurements with electrophysical and meteorological characteristics of the lower atmosphere at the stage of earthquake preparation and typhoon initiation. The model suggests that the numerous effects in the cosmic plasma have a single source: a change in the conduction current flowing in the atmosphere–ionosphere circuit.

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1. INTRODUCTION

The results of experimental studies conducted on satellites show that there is coupling between the Earth's lithospheric processes and electromagnetic and plasma disturbances in the ionosphere. The observation results were discussed in a number of reviews (Hochberg et al., 1988; Liperovskii et al., 1992; Molchanov, 1993; Ruzhin and Depueva, 1996; Buchachenko et al., 1996; Varotsos, 2001; Seismo Electromagnetics, 2002). The nature of numerous ionospheric and electromagnetic precursors of earthquakes can be understood by studying the physical processes and by constructing a model for the impact of seismic processes on the ionospheric plasma.

It has been believed that this impact is accomplished mainly by internal gravity waves (IGWs) and the electric field. The observational results are interpreted by the effects of the propagation of IGWs or the electric field appearance. Hochberg and Shalimov (2000) analyzed the existing experimental data obtained at the final stage of earthquake preparation. These authors believe that the appearance of ionospheric irregularities a few days before strong earthquakes is caused by the propagations of IGWs through the ionosphere. These waves can arise from longwave oscillations of the Earth, the local greenhouse effect, and the nonstationary mass influx of lithospheric gases. Molchanov et al. (2004) presented a concept of mechanisms of atmospheric and ionospheric phenomena. These authors believe that the migration of bubbles in the deep fluid matter can lift the hot water and gas up to the soil surface and cause earthquakes in their preparation area. Since the bubble occurrence times and coordinates have random values, the earthquakes themselves and their geochemical anomalies and foreshocks are random events. The disturbances of atmospheric temperature and density result from the hot water and gas uplift on the eve of an earthquake. This leads to the generation of atmospheric gravity waves with a period ranging from 6 to 60 min.

The interpretation of observed earthquake precursors on the basis of the IGW propagation model involves a number of difficulties. These waves propagate at an angle to the Earth's surface. The longer the period is, the smaller the angle is. The IGWs reach ionospheric heights approximately 1000 km away from the epicenter. However, there exist plasma and electromagnetic disturbances localized in the vicinity of the epicenter. Some difficulties arise when the IGW propagation effect is believed to explain the emergence of the quasi-static electric field in the ionosphere, small-scale plasma irregularities and longitudinal currents over the earthquake epicenter, the sources of VHF radio emission in the troposphere, and other phenomena. The existing theory of IGWs fails to explain the lower ionospheric oscillations with periods of 10–12 and 20–25 min detected by Rozhnoy et al. (2005) via an analysis of the spectrum of the recorded disturbance of the amplitude and phase of a signal transmitted with a frequency of 40 kHz.

An alternative factor affecting the ionosphere is the electric field. Its generation and the phenomena accompanying it in the atmosphere–ionosphere system have been actively studied in recent years. This paper considers the results of these studies, which serve as the physical basis for the model of lithosphere–ionosphere coupling.

2. QUASI-STATIC ELECTRIC FIELD IN THE ATMOSPHERE–IONOSPHERE SYSTEM

Quasi-static electric fields of an amplitude of ~10 mV/m associated with earthquake preparation were first detected by Chmyrev et al. (1989). Analyzing the records of the vertical component of the electric field *Ez*, these authors showed that the electric field in a disturbed magnetic tube 15 minutes before the earthquake increases by ~(7–8) mV/m. The quasi-static fields were studied in detail on the basis of direct satellite measurements over the Earth's seismic areas in (Gousheva et al., 2006, 2008, 2009). Hundreds of seismic events were analyzed to identify a relevant anomalous increase in the electric field in the ionosphere. These studies considered seismic sources of different magnitudes, in different tectonic structures, and at different latitudes. Orbits with a distance of less than 25° away from the epicenter and periods with a magnetic activity index of less than 5 were considered. Statistical analysis of the satellite data enabled the authors to conclude that the there is a quasi-static seismic electric field in the ionosphere. The length of the electric field disturbance in the ionosphere with an amplitude of around 10 mV/m can be up to 15 days. The disturbance of the electric field for nocturnal and daytime observations in the ionosphere has the same order of magnitude. Electric field disturbances in the ionosphere over typhoon areas were found in the studies (Isaev et al., 2002; Sorokin et al., 2005a). Thus, the satellite data make it possible to conclude that large-scale seismic and meteorological events are accompanied by a disturbed quasi-static electric field in the ionosphere with an amplitude of ~ 10 mV/m and a length of tens of hours to tens of days.

The data of direct observations of the quasi-static electric field in the ionosphere are consistent with the results of numerical modeling of the ionospheric disturbance emerging on the eve of an earthquake. The spatial distribution of the total electron content (TEC) obtained from GPS-receivers in a seismic area is analyzed. The background electric field is appended by the disturbed electric field, which leads the TEC disturbance to coincide with the observed disturbance in the area of earthquake preparation (Zolotov et al., 2008; Klimenko et al., 2011; Namgaladze et al., 2009). These studies posited that the TEC disturbance can be caused by the vertical drift of plasma under the action of the zonal electric field. Numerical simulation showed that its amplitude is (3–9) mV/m.

Along with the studies mentioned above, observations of the behavior of the electric field on the Earth's surface in seismic areas were performed (Nikiforova and Michnovski, 1995; Vershinin et al., 1999; Hao, 1988; Hao et al., 2000; Rulenko, 2000). Analysis of these studies showed that the earthquake preparation period involves short (with a length of a few to tens of minutes) local bursts of the electric field of a large amplitude, up to several kV/m. However, there are no clear electric field disturbances exceeding the background values with a length of several days observed simultaneously at horizontal distances of tens or hundreds of kilometers.

The emergence of the electric field in the atmosphere is indirectly confirmed by observations of the propagation of a VHF radio emission from sources located in the troposphere over the area of earthquake preparation (Vallianatos and Nomicos, 1998; Ruzhin et al., 2000; Ruzhin and Nomicos, 2007). The earthquake epicenters were located beyond the horizon. Long-term observations indicated that the radiation sources were at heights of 1 to 10 km. These sources include electrical discharges resulting from the formation of breakdown electric field at these heights during a few days before the earthquake. Thus, the data of direct and indirect observations of the quasi-static electric field make it possible to formulate its properties as follows.

(1) The seismic activity leads to an increase in the quasi-static electric field in the ionosphere by ~10 mV/m.

(2) The field is localized in the ionosphere over the epicenter area and the related region with a characteristic horizontal scale of 100 to 1000 km.

(3) The length of the field growth in the ionosphere before the earthquake reaches to 10–15 days.

(4) Quasi-static electric fields with similar characteristics are observed over typhoon areas.

(5) The magnitude of the vertical component of the electric field of the same spatial and temporal scales on the Earth's surface in the seismic area does not exceed the background values of ~100 V/m.

(6) The field in the daytime and nighttime ionosphere has the same order of magnitude.

It should be noted that the field amplitude reaches to 10 mV/m in the ionosphere and breakdown values in the troposphere; it simultaneously does not exceed its background values on the Earth's surface. Any model of the quasi-static electric field associated with seismic activity must meet the properties listed above.

3. ELECTRODYNAMIC MODEL OF THE QUASI-STATIC ELECTRIC FIELD PENETRATION INTO THE IONOSPHERE

Using the electrodynamic model, we obtained a mechanism to generate the quasi-static electric field in the ionosphere on a horizontal scale of 100 to 1000 km and a length of tens of hours to tens of days (Sorokin, 2007; Sorokin and Chmyrev, 2010; Sorokin et al., 2014; Sorokin and Hayakawa, 2013, 2014). The electric field is quasi-static if the characteristic time of its change is significantly larger than the discharge relaxation time in the surface atmosphere $\tau \sim \varepsilon_0/\sigma \sim$ 10–30 min (where ε_0 is the electric constant and σ is the atmospheric conductivity). In this case, the atmosphere is assumed to be a conductor with a conductivity that increases with height. The electric field in the atmosphere testifies that the electric conduction current flows there. The quasi-static electric field in the ionosphere over a seismic area can be changed in two methods. First, the load resistance in the global atmosphere–ionosphere chain can be changed and, second, the additional electromotive force (EMF) can be included in the chain.

Let us consider the first method. Approximately 80% of the load resistance of the circuit is concentrated in the lower atmosphere, which is affected by the processes of earthquake preparation. This resistance changes as a result of the injection of radioactive substances, chemically active species, and aerosols into the atmosphere and the change in the aerosol size distribution and state of the atmosphere. Finally, all of these processes change the conductivity of atmospheric surface layers. The studies (Sorokin and Yashchenko, 1999, 2000a, 2000b, Sorokin et al., 2001a) describe calculations of the change in the height distribution of the electric field in the Earth–ionosphere layer as a result of an increase in the conductivity of the lower atmosphere by alpha-particles and gamma-ray quanta arising from increased levels of atmospheric radioactivity. It was shown that the field at ionospheric heights can change 1.5–2 times with an increase in conductivity near the Earth's surface. Since the current field of fair weather in the undisturbed ionosphere of a magnitude of 10^{-3} mV/m is considerably less than its background value in the ionosphere ~0.1–1 mV/m, its change by two times will not affect it. These results were confirmed by the study (Omori et al., 2007). The results described in these papers make it possible to conclude that any models of the quasi-static electric field formation in the ionosphere on the basis of changed conductivity of the atmosphere (including by radon) contradict the experimental data and cannot serve as the basis for the mechanism of lithosphere–ionosphere coupling.

The second method of the formation of quasi-static electric field disturbance in the ionosphere is as follows. When an external EMF source associated with the earthquake preparation is included in the global circuit, the vertical current in the atmosphere and the electric field in the ionosphere over the seismic area vary. The EMF can be in the lithosphere, in the atmosphere, or in the vicinity of the lithosphere–atmosphere boundary.

If the EMF is located in the lithosphere, the field penetrates into the ionosphere through the atmosphere. In the layer between the Earth and the ionosphere, the atmosphere is a conductor with height-dependent conductivity. This layer is a section of the closed global atmosphere–ionosphere electrical circuit. The field in the ionosphere is controlled by the given spatial distribution of the amplitude of its vertical component on the Earth's surface (Kim and Hegai, 1999; Pulinets et al., 2000, 2003; Denisenko et al., 2008; Ampferer et al., 2010). The calculations performed in these studies showed that the field in the night ionosphere can reach (0.1–1) mV/m if its value on the Earth's surface is tens of kilovolts per meter on the horizontal scale of around 100 km. There are no such fields that exist for a few days. If the field on the Earth's surface is assumed to be ~100 V/m, its value in the ionosphere will be 10^{-3} mV/m. This model contradicts the experimental data mentioned above. To explain the experimental data with the model discussed above, one should suppose that the field on the Earth's surface increases by at least 10^4 times and its value is conserved for a few days at horizontal distances of hundreds of kilometers. The measurements of the electric field on the Earth's surface do not confirm this supposition. The studies discussed above make it possible to conclude that the location of the EMF in the lithosphere or in the atmosphere cannot explain the emergence of the quasi-static electric field with an amplitude of 10 mV/m and a horizontal scale of 100–1000 km in the ionosphere that acts for a few days. In addition, one should explain the concurrent absence of a considerable disturbance in the field with the same characteristics on the Earth's surface.

It seems likely that the results of observations of the quasi-static electric field of seismic origin in the ionosphere can be explained only by a conceptually different model that has been actively developed in recent years (Sorokin et al., 2001c, 2005b, 2007, 2014; Sorokin and Chmyrev, 2002, 2010; Sorokin, 2007; Sorokin and Hayakawa, 2013, 2014). The model is based on the assumption that earthquake preparation involves an additional source of current in the global circuit associated with the earthquake preparation. The EMF area is formed on atmospheric surface layers and contains the atmosphere–lithosphere interface. In this case, the electric field observed on the Earth's surface is located within the EMF. Figure 1 shows the EMF formation scheme. The EMF arises from the uplift and gravitational settling of charged aerosols injected into the atmosphere by soil gases under enhanced seismic activity. The extraneous current of the EMF decreases with height, while the conduction

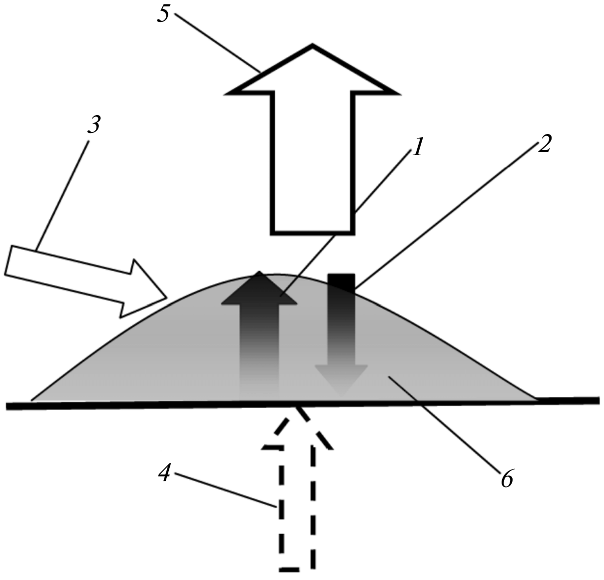

Fig. 1. Schematic of EMF formation in the surface layer. (*1*) Aerosol transport due to atmospheric convection and turbulent diffusion, (*2*) gravitational settling, (*3*) atmospheric radioactivity, (*4*) soil gases, (*5*) Electric conduction current, and (*6*) extraneous EMF current.

current increases. Here, the total current in the circuit remains unchanged with height. The conduction current near the Earth's surface can be close to the current of fair weather, and the extraneous current exceeds its value by four–five orders of magnitude. Consequently, the density of conduction current at ionospheric heights is close to the density of extraneous current near the Earth's surface. The horizontal component of the field $E_1 \sim 10$ mV/m in the ionosphere corresponds to the density of conduction current $j \sim \sigma_1 E_1 \sim 10^{-8}$ A/m^2. As is shown in (Sorokin et al., 2001c), the conduction current flowing through the atmosphere near the Earth's surface can have a value of 10^{-12} A/m^2 and, accordingly, the field can have a value of ~ 100 V/m. This fact can be illustrated by a simple estimate. The equation of continuity of the total current in the atmosphere has the form $\nabla \cdot (\sigma \mathbf{E} + \mathbf{j}_e) = 0$, where $\mathbf{j}_e$ is the extraneous current of the EMF. In the one-dimensional case, the field E_1 in the ionosphere with conductivity σ_1, can be estimated as $\sigma_0 E_0 + j_{e0} = \sigma_1 E_1$. This equation yields $E_1 = E_0(\sigma_0/\sigma_1)(1 + j_{e0}/\sigma_0 E_0)$, where j_{e0}, and E_0 are the density of extraneous current of EMF and the tension of the electric field near the Earth's surface, respectively and σ_0 is the conductivity of the lower atmosphere. If we assume for example that the extraneous current is conditioned by the motion of aerosols with concentration N and charged with Ze under the action of vertical convection of the atmosphere with a rate v, the extraneous current can be estimated by the formula $j_{e0} \approx ZeNv$. The charge of aerosols in the atmosphere ranges from $100e$ to $1000e$. Taking $Z = 3 \times 10^2$, $N = 8 \times 10^9$ m^{-3}, $v = 0.3$ m/s, we estimate of the field in the ionosphere as $E_1 \approx 10^{-6}\ (1 + 10^4)$ V/m $\approx$ 10 mV/m. It follows even from this rough estimate that the choice of a model of the penetration of the field (generated by the EMF located in the lithosphere or in the atmosphere) into the ionosphere leads to the loss of four orders of magnitude of the field in the ionosphere.

Lithospheric activity stimulates processes that are accompanied by electric field generation. Increased concentrations of charged aerosols by one or two orders of magnitude, as well an increased level of atmospheric radioactivity due to the injection of radon and other radioactive substances into the atmosphere, are observed days or weeks before the earthquake (Alekseev and Alekseeva, 1992; Virk and Singh, 1994; Heincke et al., 1994; Voitov and Dobrovolsky, 1994; Pulinets et al., 1997; Yasuoka et al., 2006; Omori et al., 2007). King (1986) analyzed data on the injection of soil gases (such as radon, helium, hydrogen, and carbon dioxide) into the atmosphere; they arise in the epicenter area with a radius of 500 km during a time period ranging from several hours to several weeks before the earthquake. A fivefold jump in the groundwater radon concentration a week before the earthquake was found in (Igarashi et al., 1995). Significant aerosol emissions of metals Cu, Fe, Ni, Zn, Pb, Co, and Cr and radon were found in (Boyarchuk, 1997). The quasi-static electric field in the ionosphere is disturbed simultaneously with the emissions of active substances into the lower atmosphere. The formation mechanism of

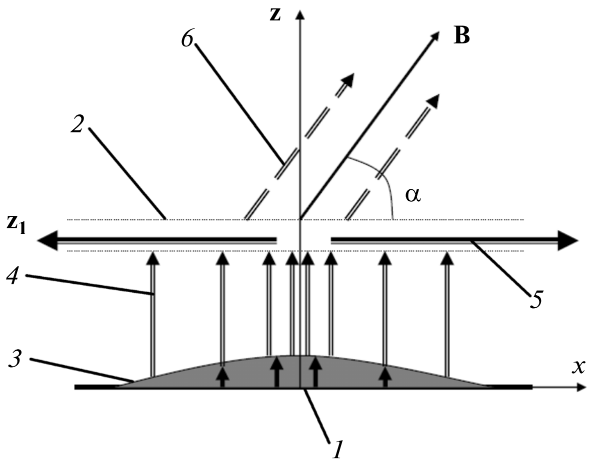

Fig. 2. Schematic of the formation of quasi-static electric field (Sorokin et al., 2005a). (*1*) The Earth's surface, (*2*) Conductive ionosphere, (*3*) Extraneous EMF current in the surface atmosphere, (*4*) conduction current in the atmosphere–ionosphere circuit, (*5*) longitudinal current, (6) satellite trajectory, and (*7*) soil gases.

the extraneous EMF current caused by the dynamics of charged aerosols in surface atmospheric layers was considered in (Sorokin and Yaschenko, 1999, 2000a, 2000b). An EMF can arise when the emission of charged soil aerosols from the lithosphere into the atmosphere is intensified or when the meteorological conditions are changed under their stable height distribution. The quasi-static height distribution of aerosols can result from their convective and turbulent transport upwards and gravitational settling. Turbulent transport occurs due to the vertical gradient of horizontal wind, when the kinetic energy of wind is converted into the energy of turbulent pulsations, as well as under thermal instability of the atmosphere, when the negative gradient of temperature exceeds its adiabatic gradient. Turbulent eddies transport aerosols from the heights where their concentration is high to the heights where their concentration is low. Equilibrium is reached when the vertical flow of aerosols is balanced by their gravitational settling.

Sorokin et al. (2001c) obtained an equation for the function of aerosol particle distribution by electric charge and height. This function gives the probability that the particle has a charge *Ze* at time *t* and at height *z*. Using the moments of the distribution function, the authors of this study obtained an equation for the vertical component of extraneous current density. The resulting estimate of the extraneous EMF current showed that the proposed mechanism makes it possible to obtain the observed current density in the ionosphere ~10^{-8} A/m^2. In many cases, the soil aerosols are injected into the atmosphere, together with radioactive substances, which additionally ionize the atmosphere. The ionization increases its conductivity. The injection of aerosols decreases the conductivity due to the adherence of ions to aerosols. In addition, the interaction of ions with charged aerosols changes the charge on them. This leads to a change in the extraneous EMF current generated during the injection of aerosols into the atmosphere. The first theoretical investigation of these processes is performed in (Sorokin et al., 2007), where the height distribution of ion formation rate *q* was found; these ions arise from the absorption of gamma-radiation and alpha-particles of radioactive decay in the air. The stationary structure of ions in the atmosphere was calculated on the basis of ionization–recombination processes. This system involves the processes of ionization and recombination, the transfer of ions under the action of an electric field, and interaction with charged aerosols. This system has an additional equation for the transport of charged aerosols. The aerosols are transported upwards by atmospheric convection and due to turbulent diffusion. Aerosols decrease the atmospheric conductivity due to the adherence of ions to them. These theoretical studies revealed that the concentration of charged aerosols, the atmospheric conductivity, the EMF, and the electric field near the Earth's surface are interdependent. A system of nonlinear equations was obtained for these variables in that study. The calculations showed that the increase in the aerosol concentration in the atmosphere leads to decreased conductivity due to the loss of light ions by their adherence to aerosols.

Sorokin et al. (2005b, 2007) showed that the extraneous EMF current depends on the conductivity and the vertical component of the electric field generated on the Earth's surface. Ground-based observations revealed no significant simultaneous changes in the quasi-static electric field in seismically active areas with a horizontal scale of hundreds to thousands of kilometers that last for a few days. Consequently, the possible disturbances in the field should not exceed its background values of ~100 V/m. As was shown in (Sorokin et al., 2005b), this limitation on the field magnitude on the Earth's surface is caused by the mechanism of feedback between this field and the extraneous EMF current, which generates the electric field. The feedback between the EMF and the electric field arises from the formation of a potential barrier on the lithosphere–atmosphere boundary when the charged aerosols move upward and cross this boundary. With this feedback, the extraneous current on the Earth's surface depends on the vertical component of electric field on its surface. The analysis of this field-limitation mechanism conducted in (Sorokin et al., 2005b; 2007) showed that the vertical component of the electric field for any value of the extraneous EMF current does not exceed a certain maximum (around 90 V/m).

The calculations showed that the extraneous current is largely concentrated at heights of up to 10 km. Its value near the Earth can be (10^{-8} to 10^{-6}) A/m^2. The current decreases with a growth in the level of atmospheric radioactivity. This dependence is due to the changed conductivity of ionized air. The theory of the generation of a quasi-static electric field of seismic origin that is consistent with direct and indirect observations of the field in the ionosphere, atmosphere, and on the Earth's surface was developed first in (Sorokin et al., 2001c, 2005b, 2005c, 2007). The field is associated with the disturbance of electric conduction current in the global atmosphere–ionosphere circuit. This disturbance is caused by the EMF involved in the global circuit. The EMF arises from the injection of charged aerosols into the atmosphere, their vertical transport, and gravitational settling. Figure 2 shows the schematic of the formation of electric current in the global circuit. The theory implies a self-consistent system of nonlinear equations for calculating the spatial distribution of the extraneous current, electric field, atmospheric conduction, and concentrations of ions and charged aerosols. A method for calculating the spatial distribution of the electric field was developed (Sorokin et al., 2005c, 2006a). Figure 3 shows an example for the calculation of the spatial distribution of the field in the ionosphere and on the Earth's surface. The calculation results show that the horizontal component of the field in the ionosphere reaches ~10 mV/m, while the vertical component of the field on the Earth's surface is limited to a value of ~100 V/m. Sorokin et al. (2011, 2012a, 2012b) conducted theoretical studies of the spatial distribution of the quasi-static electric field in the atmosphere. The theory-based calculations of the spatial distribution of the ratio of the electric field to its breakdown value showed that the troposphere may have areas under some conditions where the field reaches the breakdown value. Figure 4 shows an example of the spatial distribution of the electric field with an indication of the area (for $E/E_k > 1$) where the field reaches the breakdown value. This area contains one or two layers of a thickness of 1–2 km located at a height of 10 km. The characteristics of these layers are determined by atmospheric and aerosol parameters. With an increasing rate of vertical convection of the atmosphere, the height of the breakdown field area in the lower troposphere increases and then a second layer appears above (at a height of 10 km). In this case, the lower layer disappears.

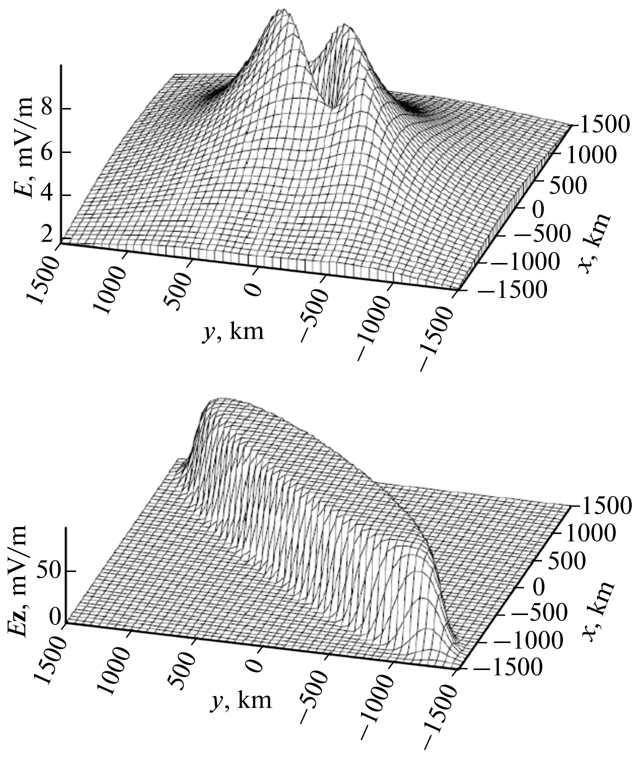

Fig. 3. Spatial distribution of the electric field calculated for the angle $\beta = 45°$ of the orientation of fault axis relative to the magnetic meridian plane (Sorokin et al., 2006b). Upper panel: horizontal component of the electric field in the ionosphere; the angle of magnetic field inclination is 20°. Bottom panel: vertical component of electric field on the Earth's surface.

4. IONOSPHERIC IRREGULARITIES ASSOCIATED WITH CURRENT DISTURBANCE IN THE AMOSPHERE–IONOSPHERE ELECTRIC CIRCUIT

The quasi-static electric field (with a magnitude reaching 10 mV/m in the ionosphere) stimulates the development of plasma and electromagnetic effects. The growth of the electric field leads to instability of acoustic–gravity waves (AGWs) in the ionosphere (Sorokin et al., 1998; Sorokin and Chmyrev, 1999a). This instability is associated with the conversion of heat emitted by ionospheric current into wave energy. The distribution of AGWs in this medium is accompanied by disturbed conduction of electric current. Under certain conditions, the heat generated by electric current leads to an increase in the AGW amplitude. The energy of this instability is caused by the EMF of the extraneous electric field. The field energy is converted into the wave energy without changing the heat balance of the medium. The critical field magnitude is determined from the fact that the amount of heat energy of disturbed current is equal to the amount of dissipation energy due to magnetic viscosity. If the field is less than the critical field, the initial disturbance attenuates; if the field exceeds the critical field, a wave buildup occurs. An estimate shows that the critical field magnitude is (6–10) mV/m. The exponential growth of the AGW amplitude in the electric field in the ionosphere is limited by the vortex formation. This nonlinear stage of wave instability development was considered in (Chmyrev and Sorokin, 2010); here, nonlinear equations for the low-frequency branch of AGWs were obtained. In the nonlinear stage of disturbance propagation, the field transforms the AGW into a dipole vortex. If the electric field exceeds the threshold value, solitary dipole vortex structures are generated in the lower ionosphere.

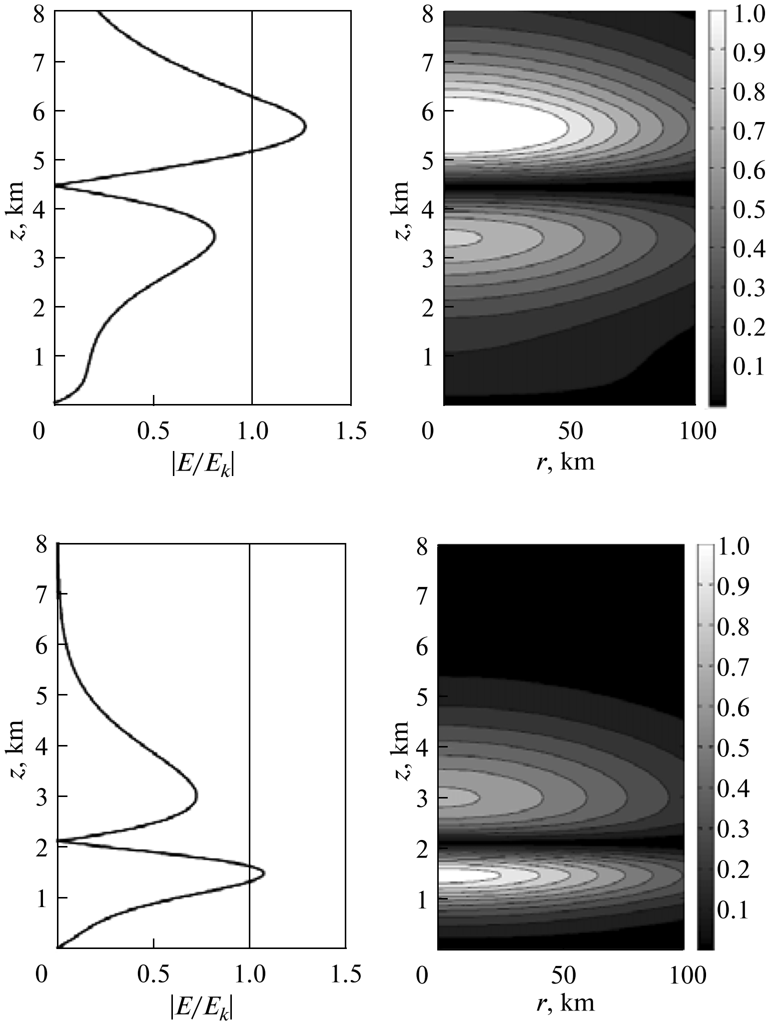

Fig. 4. Spatial distribution of the ratio of the vertical component of the electric field to its breakdown value.

Simultaneously with plasma disturbance in the vortex, its conductivity changes, which leads to the formation of horizontal irregularities of conductivity in the conductive layer of the lower ionosphere. These irregularities are accompanied by the formation of plasma irregularities in the upper ionosphere along the magnetic field (Sorokin et al., 1998, 2000; Sorokin and Chmyrev, 1999a). The appearance of conductivity irregularities in the ionospheric *E*-layer in the presence of extraneous electric field leads to the formation of an electric field of polarization. The high conductivity along magnetic lines of force leads to polarization field propagation in the upper layers of the ionosphere and in the magnetosphere. The arising electrical circuit includes the longitudinal currents and transversal currents that are closed on them. The longitudinal currents transfer the electric field upward along magnetic lines of force. The transversal currents arise in the ionosphere due to the Pedersen conductivity. Since the longitudinal currents are transferred by electrons and the transversal currents are carried by ions, the electric field propagation along the magnetic lines of force the appearance of closing currents are accompanied by local changes in the plasma concentration. These plasma irregularities are extended along the magnetic field. Figure 5 shows a schematic of the satellite recording of plasma density fluctuations and VLF-oscillations of the geomagnetic field. When the satellite crosses plasma irregularities of horizontal scale l with a speed of around 8 km/s, plasma density fluctuations with a period $\Delta t \approx (0.4–4)$ s are recorded. Since these irregularities are caused by longitudinal currents, geomagnetic oscillations with the same period are recorded during their crossing by the satellite. Their amplitude b is $b \approx 5$ nT. The theoretical studies made it possible to formulate a mechanism for the formation of horizontal periodic irregularities in the lower ionosphere and plasma layers extended along the magnetic field. During earthquake preparation in a magnetic tube with its base covering the seismic area, the quasi-static electric field increases in line

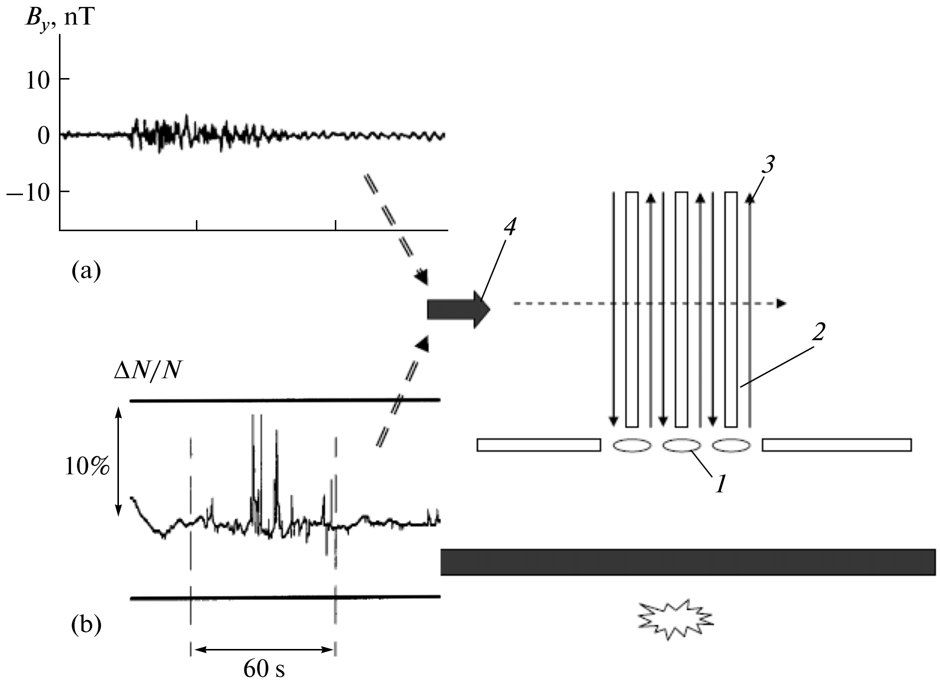

Fig. 5. Schematic of the formation of plasma layers and longitudinal currents in the upper ionosphere caused by the polarization of horizontal irregularities of the lower ionospheric conductivity by the electric field. (*1*) Irregularities of conductivity, (*2*) plasma layers, (*3*) longitudinal current, and (*4*) satellite trajectory.

with the above-described mechanism. When its value exceeds some critical value ~5–10 mV/m, horizontal periodic irregularities appear in the lower ionosphere, and plasma layers extended along the magnetic field appear in the upper ionosphere. This mechanism is confirmed by direct satellite measurements of electric field and plasma density (Chmyrev et al., 1997, 1989). The results of simultaneous observations of the increased electric field and the formation of plasma irregularities in the magnetic tube with its base covering the typhoon formation area can be found in (Sorokin et al., 2005a). It was shown that the field in the disturbed magnetic tube is amplified up to 15 mV/m and plasma irregularities with a transverse spatial scale of 10–20 km arise. These results recur for some ten events. Although the sources of quasi-static field generation in the ionosphere are different, the formation of irregularities is the same.

Amplification of the electric current and the appearance of the Ampere force in the ionospheric *E*-layer lead to a specific mechanism that filters background IGWs propagating from the atmosphere into the ionosphere (Sorokin and Pokhotelov, 2010a, 2010b, 2014). The field effect on gravity waves is associated with the appearance of the Ampere force in the ionosphere, which influences the neutral component of ionospheric plasma in the spectral range of these waves. This influence results in the appearance of a discrete spectrum of oscillations in the ionosphere, the maximum periods of which increase almost like natural numbers. These specific features of ionospheric waves are confirmed by observations. Rozhnoi et al. (2005) found the maxima of spectral disturbance of the amplitude and phase of the transmitter signal with a frequency of 40 kHz, with periods of 10–12 and 20–25 min.

Disturbance of the electric current in the global circuit with the appearance of additional EMF is accompanied by a modification of the ionosphere. The mechanism of the disturbance of the concentration of electrons and ions in the *D*-region of the ionosphere was considered in (Laptukhov et al., 2009). This model considers the effect on a disturbance of the transport of electrons and ions in the *D*-layer under the effect of electric field and heating of the electron component of plasma by the field. This disturbance in the *D*-region arises due to both the transfer of electrons and ions by the current and the heating of electrons. The upper part of the layer contains free electrons, and the lower part contains negatively charged ions arising from the rapid adherence of electrons to neutral molecules. The electric current flow, which is due to a transfer and change in the type of charge carriers, leads to the formation of a layer of increased electron concentration. Figure 6 shows the calculated spatial distribution of the electron concentration obtained in (Laptukhov et al., 2009). The transfer of electrons downward leads to an increase in the plasma density at heights below 70 km. This occurs due to the fact that all electrons do not manage adhere to neutral mole-

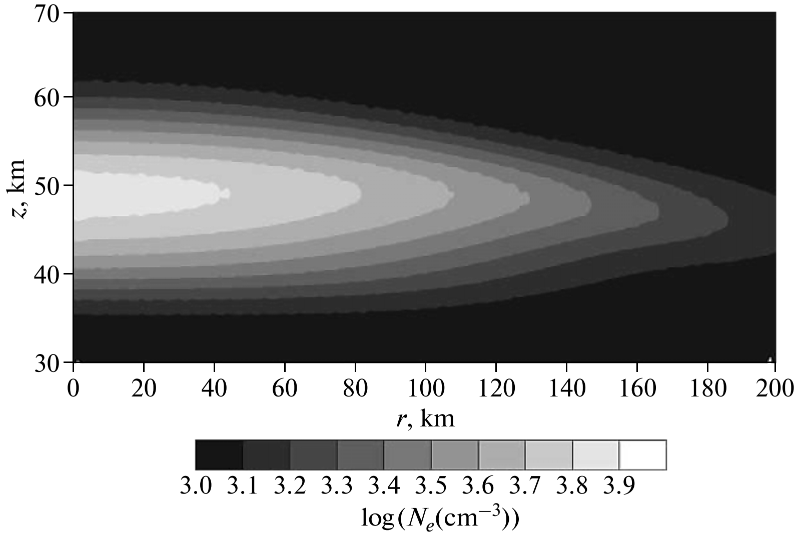

Fig. 6. Spatial distribution of the concentration of electrons in the ionospheric *D*-region arising from disturbed electric current in the global circuit (Laptukhov et al., 2009).

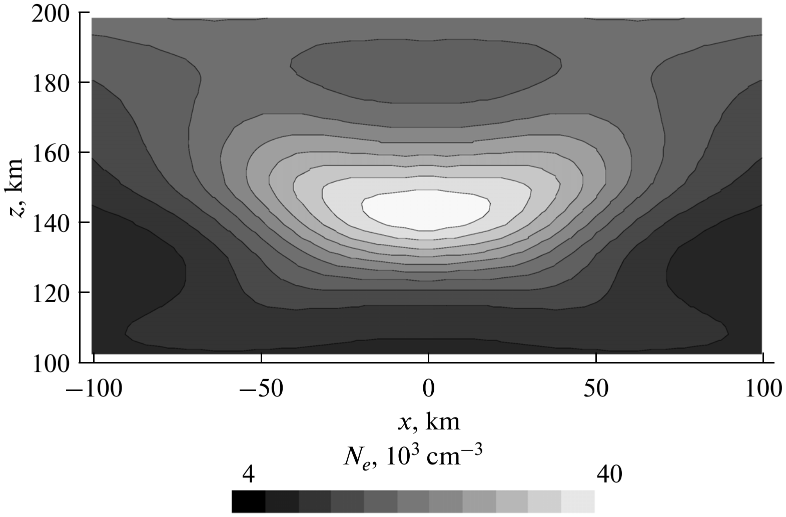

Fig. 7. Spatial distribution of electrons in the ionospheric *E*-layer in the disturbance area of electric current in the global circuit (Sorokin et al., 2006a, 2006b).

cules at lower heights. The concentration of electrons and ions at these heights can increase by an order of magnitude. This model for the modification of the ionospheric *D*-region over the epicenters of earthquakes in the making is confirmed by the results of (Hayakawa et al., 2005; Nickolaenko et al., 2006). These studies found anomalous effects from observations of Schumann resonances near seismically active areas. Since the parameters of Schumann resonances depend on the properties of the Earth–ionosphere waveguide, this effect was interpreted as a result of the changed ionization degree in the *D*-layer.

Disturbance of the electric current at a part of the global circuit over a seismic area leads to a modification of the *E*-layer, including the formation of a sporadic layer. A theoretical model for the disturbance of the lower ionosphere above the *D*-layer was considered in (Sorokin et al., 2006b). This study developed a method for calculating the spatial distribution of the concentration of electrons in the lower ionosphere arising from the EMF in the atmospheric surface layer. Amplification of the electric current flowing between the Earth and the ionosphere was shown to increase the plasma density in the *E*-layer. An example of the calculated spatial distribution of the electron concentration is shown in Fig. 7. The calculations revealed that the horizontal electric field of conduction current in the ionosphere generates a thin layer of electron concentration due to the drift of long-lived metal ions to the center of the disturbed area. This layer can be recorded as an anomalous sporadic *E*-layer. Consequently, the emergence of EMF in the lower atmosphere over the area of earthquake preparation leads to the formation of both regular and sporadic layers in the ionospheric *E*-region.

Disturbance of the electric current in the global circuit over a seismic area leads to a significant modification of the ionospheric *F*-region. Ruzhin et al. (2014) found a mechanism of the disturbance of the total electron content (TEC) of the ionosphere during the amplification of seismic activity. The spatial distribution of TEC disturbance was shown to result from heating of the ionosphere by the electric current and from the plasma drift in the electric field of this current. The increase in the electric field and the related increase in the amount of heat released in the ionospheric *E*-layer as a result of the electric current flow leads to a growth in temperature of the *F*-region (Sorokin and Chmyrev, 1999b). The heating of the ionosphere increases the scales of the height distribution of ionospheric components and, therefore, the height profile of the *F*2-layer. This leads to a spatial distribution of the TEC disturbance of the same sign. The ionosphere heating when an electric field of ~1–10 mV/m arises leads to a relative change in the TEC by the same value as the plasma drift in this field. The total spatial distribution of the TEC is the sum of these two factors, and its character depends on the ratio between them. The current appears in the global atmosphere–ionosphere circuit when the atmospheric surface layers involve the EMF, which is associated with the dynamics of charged aerosols injected into the atmosphere. This model makes it possible to calculate the spatial distribution of the TEC in the ionosphere for a given horizontal distribution of the concentration of charged aerosols on the Earth's surface.

5. ELECTROMAGNETIC EFFECTS ACCOMPANYING THE CURRENT DISTURBANCE IN THE ATMOSPHERE–IONOSPHERE ELECTRIC CIRCUIT

The electric current disturbance in the global circuit over a seismic area is accompanied by the formation of tropospheric layers, where the electric field can reach breakdown values. The calculated spatial distribution of the electric field that reached this value is shown in Fig. 4. Sorokin et al. (2011, 2012a, 2012b) developed a theory on the generation of electromagnetic disturbances arising from random electrical discharges in the troposphere, where the electric field reaches a breakdown value. Since the breakdown electric field in the atmosphere depends on its density and each turbulent vortex involves density fluctuations, those vortices in which the magnitude of the extraneous electric field is compared to its breakdown value have an emerging electric discharge. Thus, the turbulence results in random electrical discharges of a size of almost the spatial scale of the turbulent vortex. The calculations showed that the spectrum of electromagnetic radiation of random discharges covers the VHF range from ~10 to 100 MHz. The field amplitude at a distance of 300 km from the epicenter of the seismic area is ~6 V/m. The spectral maximum depends on the frequency of discharges, and the spectral form is determined by the time of growth and decline of the current wave in the discharge. In addition to intrinsic electromagnetic radiation, the emergence of random discharges in the troposphere leads to a series of electromagnetic and optical phenomena. The region where random discharges are generated scatters radiowaves in the VHF range, because each discharge is a conductor with high conductivity and a sufficiently short lifetime (Sorokin et al., 2013). Preliminary estimates showed (Sorokin et al., 2012a, 2012b) that the field of the discharge-scattered wave of the VHF-transmitter with a frequency of 100 MHz and a capacity of ~10–100 kW can reach a magnitude of ~10–50 μV/m at a distance of more than 100 km from the disturbed area. Electrical discharges in the troposphere generate optical radiation in the visible range of the spectrum. Due to the sufficiently high frequency of their appearance, an averaged stationary glow of the disturbed area can be expected. Preliminary estimates showed that the intensity of radiation of the tropospheric region in which random discharges appear can reach ~9 kR. The luminosity was estimated by the quantum energy of 4×10^{-19} J emitted by the discharge area, which corresponds to the middle of the visible light spectrum. The appearance of the quasi-static electric field in a sufficiently thin layer of the troposphere leads to its heating. Preliminary estimates showed that the density of heat energy release is 0.001–0.01 W/m^3. If the disturbed area thickness is ~1 km, the surface density of the released heat is 1–10 W/m^2. This heat release leads to the warming of this atmospheric layer by 1–3 K per day. The appearance of discharges leads to an increased ozone concentration and the formation of outgoing upward infrared radiation. The electromagnetic and optical phenomena considered above, which accompanies the appearance of electrical discharges in the troposphere, can be detected by satellites and serve as a source of data on the development of seismic processes. Figure 8 shows a schematic of the processes accompanying the appearance of random electrical discharges in the tropospheric layer where the electric field reaches a breakdown value. The results obtained from the theoretical studies considered above are confirmed by observations of the effect of lithospheric processes on the atmosphere and ionosphere. Some studies detected anomalous radiation in the VHF range on the eve of earthquakes with their epicenters, including both those located on land and under the sea bottom (Nomicos et al., 1995; Vallianatos and Nomicos, 1998). The signals were observed on the Earth's surface beyond the horizon at a distance of ~300 km away from the epicenter. They can be recorded only if

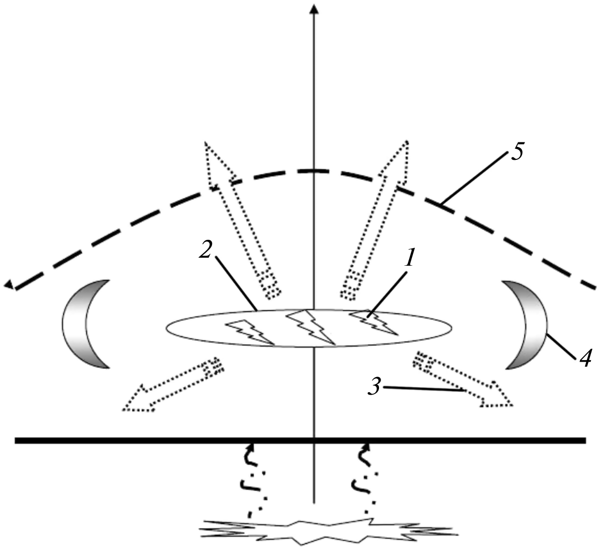

Fig. 8. Phenomena accompanying random electrical discharges in the lower atmosphere. (*1*) Random electrical discharges, (*2*) atmospheric heating in the discharge area and generation of outgoing microwave radiation, (*3*) wideband VHF radio emission observed on the Earth and in space, (*4*) glow in the visible range of the spectrum, (*5*) refraction and scattering of VHF radiowaves in the troposphere, leading to receipt of transmitted signals beyond the horizon on the Earth and on the satellite, and (*6*) increase in ozone concentration in the disturbed area.

the radiation source is located in the atmosphere above the Earth's surface. Based on these data, Ruzhin et al. (1999) and Ruzhin and Nomicos (2007) showed that the source of radiation in the VHF range associated with the preparation of earthquakes is located in the lower atmosphere at heights of 1 to 10 km above the epicenter of the future earthquake.

Electromagnetic precursors of earthquakes in the VHF range were actively studied in (Hayakawa et al., 2006; Yonaiguchi et al., 2007; Yasuda et al., 2009). The regular recording of signals of VHF radio broadcast stations showed that a few days before the earthquake are characterized by anomalous radio signal propagation beyond the horizon if the propagation path passes over the seismic area (Fukumoto et al., 2001; Yasuda et al., 2009; Moriya et al., 2010). It can be suggested that the region beyond the horizon has a VHF radiowave scattered at random discharges in the troposphere. Nearly the same time periods before earthquakes are characterized by an increased ozone concentration in the atmosphere (Tertyshnikov, 1996). Satellites can sufficiently reliably record the outgoing infrared radiation associated with earthquake preparation (Ouzounov et al., 2007), which can arise from either ozone emission (Kratz and Cess, 1988) or heating of the tropospheric layer where the field reaches a breakdown value.

The formation of horizontal conductivity irregularities in the lower ionosphere and plasma irregularities that are extended along the magnetic field in the area of earthquake preparation is accompanied by an enlarged spectrum of the VLF transmission signals (Chmyrev et al., 2008) and increased electromagnetic radiation in the ELF band recorded by satellites. Borisov et al. (2001) presented a mechanism associated with the radiation of whistler mode waves in the upper ionosphere, which are generated when the pulse ELF-noises are transformed on small-scale conductivity irregularities in the lower ionosphere. The electromagnetic pulses in the ELF band are excited by lightning discharges and propagate in the subionospheric waveguide with weak absorption. The horizontal component of the electric field of radiation excites polarization currents on conductivity irregularities, depending on the wave frequency. These currents act as ELF-wave sources, propagating in the whistler mode in the upper ionosphere and magnetosphere along the magnetic lines of force.

Studies (Molchanov, 1999; Surkov and Pilipenko, 1999; Sorokin and Pokhotelov, 2010b) have analyzed the formation of VLF-radiation on the Earth's surface by lithospheric sources and its possible penetration into the ionosphere (Molchanov et al., 1995). Many studies on the nature of the atmosphere–ionosphere interaction attempt to find its mechanisms. Sorokin et al. (2001b, 2003) proposed a mechanism for the generation of VLF oscillations arising from disturbed electric current in the global circuit. This mechanism is based on the generation of gyrotropic waves (GWs) in the lower ionosphere by the noise electromagnetic field in the presence of horizontal irregularities of its conductivity associated with the instability of AGWs due to an amplified electric field. These waves propagate in a thin layer of the lower ionosphere along the Earth's surface at low and midlatitudes with weak attenuation and phase velocities of tens to hundreds of km/s (Sorokin and Pokhotelov, 2005). Different sources of electromagnetic radiation generate electromagnetic noise in the range of VLF and geomagnetic pulsations. In the areas of horizontal irregularities of ionospheric conductivity, this noise leads to the appearance of polarization currents that are sources of GWs. These sources with a horizontal spatial scale of 10 km lead to the formation of narrow-banded electromagnetic radiation at the Earth's surface with a characteristic frequency of ~1–10 Hz. The calculated spectrum of the amplitude of geomagnetic disturbance showed that the relative disturbance is maximal in the ULF band and its magnitude in the epicenter reaches 20–40% of the undisturbed value. Sorokin and Hayakawa (2008) considered a mechanism of the formation of a line spectrum of geomagnetic pulsations due to the interaction of background electromagnetic noise with periodic irregularities of the ionospheric conductivity. The currents arising from this interaction are coherent sources of GWs propagating in the conducting ionospheric layer of a finite thickness. The dispersion characteristics of these waves are consid-

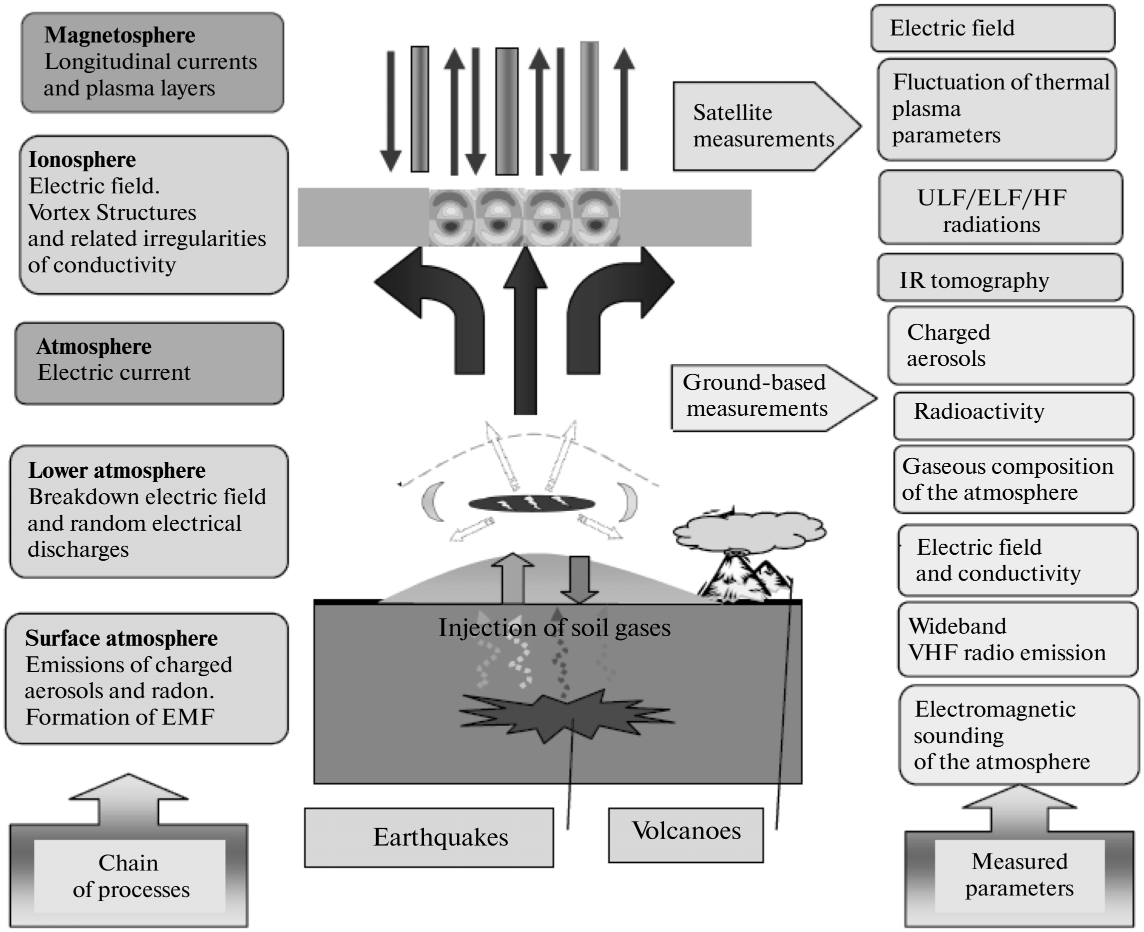

Fig. 9. Schematic of processes and recorded variables constituting the electrodynamic model of lithosphere–ionosphere coupling (Sorokin, 2007).

ered in (Sorokin et al., 2009). The spectrum of oscillations consists of narrow-banded lines in the frequency range from 1 to 30 Hz (Sorokin and Hayakawa, 2008). The characteristics of the line spectrum of electromagnetic disturbances depend on both the parameters of ionospheric irregularities and the electrophysical parameters of the ionosphere. In general, the oscillation amplitude is determined by the amplitude of ionospheric irregularities, their spatial structure, and wave absorption. The frequencies of the spectral line maxima are determined by the thickness of the ionospheric conductivity layer and the latitude. With decreasing latitude, the phase velocity of GWs increases, which leads to an increase in the frequency maxima. The width of the spectral lines is determined by the width of the spatial spectrum of ionospheric irregularities and the ratio of the Pedersen and Hall ionospheric conductivities. GW generation leads to a change in the frequency of the Schumann resonance maximum (Hayakawa et al., 2011). These mechanisms for the generation of electromagnetic emissions are confirmed by observational data. The results of ELF/VLF measurements onboard the KOSMOS-1809 satellite in the Spitak region showed (Chmyrev et al., 1997) that the intensity of ELF radiation is ~10 nT at a frequency of 140 Hz (in the bandwidth of 25 Hz) and ~3 nT at a frequency of 450 Hz (in the bandwidth of 75 Hz). Rauscher and Van Bise (1999) present the results of long-term measurements of electromagnetic oscillations in the ULF/ELF band conducted on the network of electromagnetic observatories in the United States. Narrowband line spectra of electromagnetic oscillations were recorded during the earthquake preparation and volcanic eruptions. The frequencies of the spectral line maxima measured by Rauscher and Van Bise (1999) and calculated in (Sorokin and Hayakawa, 2008) are close by magnitude.

6. CONCLUSIONS

The ionosphere, stratosphere, and troposphere constitute a unified medium in which the physical phenomena are associated with each other. According to the model presented here, the intensive processes in the lower atmosphere and lithosphere have an electrodynamic influence on ionospheric plasma. These phenomena involve earthquake preparation, volcanic eruption, typhoons, storm activity, and technogenic catastrophes. Figure 9 shows a schematic of the processes and recorded variables that constitute the electrodynamic model of lithosphere–ionosphere coupling (Sorokin and Hayakawa, 2013, 2014). For the first time, this model made it possible to explain the observations of quasi-static electric fields in the ionosphere and on the Earth's surface in a seismic area, which had not been accomplished with other models. This model allowed us to find a mechanism of amplification (with height) of the electrical conduction current flowing in the Earth–ionosphere layer and a mechanism of the limitation of the vertical component of the field on the Earth's surface. The amplification mechanism is associated with a decrease (with height) in the extraneous EMF current generated in the lower atmosphere if the total current equal to the sum of the extraneous current and conduction current is conserved. In this case, even due to an increase in conductivity with height, the field in the ionosphere can reach ~10 mV/m. The conduction current arises from the inclusion of an extra EMF in the global circuit. This force is generated in the lower atmosphere during the injection of charged aerosols by lithospheric gases and their transport in the convective atmosphere. The limitation of the field on the Earth's surface is conditioned by feedback between the extraneous current and the generated electric field. The calculations showed that the quasi-static field in the ionosphere reaches ~10 mV/m, while its value on the Earth's surface is ~100 V/m. In addition, the field can reach breakdown values at tropospheric heights of ~5–10 km in a layer of thickness of 1–2 km. The extraneous EMF current on the Earth's surface can have values of ~10^{-8}–10^{-6} A/m^2. In some sense, this model is similar to the model the IGW impact on the ionosphere. Indeed, the amplitude of IGWs increases with height due to decreased atmospheric density. Similarly, the conduction current increases with height due to decreased extraneous current. This means that the influencing factors are amplified in the ionosphere. In addition, it is difficult to distinguish IGWs from the background near the Earth's surface. Similarly, the disturbance of conduction current near the Earth does not exceed its background value, which is equal to the current of fair weather. Both of these factors have a single source: the lithospheric gases injected into the atmosphere. It can be assumed that both IGWs and electric current can affect the ionosphere simultaneously. The consequences of this effect may vary. It seems that the interpretation of experimental data should take into account the possibility of this complex effect.

Using the model, we performed theoretical studies on the plasma and electromagnetic effects accompanying the generation of conduction current in the global circuit. The calculations showed that the injection of aerosols into the atmosphere and the appearance of EMF in the global circuit lead to the stimulation of a number of observed plasma and electromagnetic effects. One should note among them the instability of AGWs in the ionosphere, the formation of horizontal vortex structures and conductivity irregularities, plasma irregularities extended along the magnetic field and longitudinal currents, and the formation of large-scale ionospheric irregularities in the *D*-, *E*-, and *F*-regions. The appearance of plasma irregularities and longitudinal currents leads to ULF-oscillations, extension of the spectrum of VLF signals, amplification of electromagnetic radiation in ELF-band, the formation of a line spectrum of electromagnetic waves in the VLF-band, a change in the frequency of the Schumann resonance maximum, and the depression of geomagnetic pulsations of magnetospheric sources in the ULF-band. The electric field increase to the breakdown value in the troposphere leads to the appearance of random electrical discharges in the troposphere, the generation of VHF radio emission, and scattering of VHF radiowave discharges.

The electrodynamic model of the effect of seismic and meteorological processes on cosmic plasma can serve as a physical basis of the satellite system for monitoring of earthquake precursors (Chmyrev et al., 2013) and the catastrophic phase of typhoon development (Sorokin and Chernyi, 1999). The model makes it possible to couple the satellite data of electromagnetic and plasma measurements with electrophysical and meteorological characteristics of the lower atmosphere at the stage of earthquake preparation and typhoon initiation. The model explains the numerous effects on cosmic plasma by a single cause: the change in the conduction current flowing in the atmosphere–ionosphere circuit. At the initial stage of seismic activity and typhoon formation (until the catastrophic phase), aerosol injection or vapor condensation over the ocean surface occurs with a redistribution of charge carriers and a change in their mobility, which, together with vertical convection, leads to the effect described above in the Earth–ionosphere electric circuit.

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