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Physical Mechanism of Ionospheric Total Electron Content Perturbations over a Seismoactive Region

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Abstract—A mechanism for the total electron content (TEC) perturbation in the ionosphere during seismic activity strengthening is proposed. The spatial distribution of the TEC perturbation is shown to be determined by the joint effect of the following two factors: the heating of the ionosphere by electric current and the plasma drift in the electric field of this current. The TEC perturbation behavior depends on the relationship between these processes. The current arises in a global electric circuit as the EMF, which is related to the dynamics of charged aerosols injected into the atmosphere, and comes into being in atmospheric surface layers. The developed model allows calculation of the spatial TEC distribution in the ionosphere for a prescribed horizontal distribution of the charged aerosol concentration at the Earth's surface.

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1. INTRODUCTION

A method for measuring the total electron content (TEC) in the ionosphere using GPS receivers has lately been intensely developed. Studies devoted to the analysis of the spatial TEC distribution prior to earthquakes are under way (see, e.g., Oraevsky et al., 2000; Liu et al., 2001; Ruzhin et al., 2002; Afraimovich et al., 2004; Zakharenkova et al., 2008; Devi et al., 2010; Klimenko et al., 2011). Pulinets (2009) tried to explain a possible modification of the ionosphere by air ionization due to radon injection into the atmosphere in the neighborhood of active faults. The process of local modification of the global electric circuit and the corresponding ionospheric variability during tectonic activity was discussed. The appearance of an additional ionization source was assumed to affect the ionospheric conductivity in two ways (Pulinets, 2009). The occurrence of additional ions enhances atmospheric conductivity and, at the same time, the formation of heavy cluster ions results in its reduction. The resulting conductivity was not calculated by Pulinets (2009). It should be noted that there exist theoretical investigations of the ionospheric conductivity modification that is due to an ionization source. The processes of conductivity formation under the action of gamma and alpha-decay sources, as applied to seismic processes, were studied in detail by Sorokin et al. (2007) based on the solution of a system of self-consistent nonlinear equations for the electric field and the ion and aerosol concentrations, with respect to their interaction and the atmospheric conductivity. Further, it is assumed by Pulinets (2009) that an anomaly of the atmospheric conductivity brings about the current variability in a local section of the circuit and, hence, the generation of a horizontal electric field in the ionosphere. The value of this field was not calculated. This concept was applied to explain a possible TEC perturbation in the equatorial region (Pulinets, 2009). Since the ionospheric field is directed eastward in the equatorial anomaly region, the field of the perturbed current strengthens the ionospheric field eastward from the epicenter and reduces it westward accordingly. Hence, the TEC should increase eastward and decrease westward from the epicenter. It is well known that the "fair weather" current is ~10^{-12} A/m^2 and the atmospheric conductivity is ~10^{-14} mho/m. Hence, the electric field is ~100 V/m at the surface of the Earth. The electric current with the ionospheric density that has a conductivity of ~10^{-6} mho/m corresponds to a field of ~10^{-3} mV/m. A two-fold change in the conductivity near the Earth's surface due to the ionization will result in a change in the current density in a local circuit section by a factor of two. Hence, an extra electric field will be three or four orders of magnitude weaker than the background ionospheric field (~(0.1–1) mV/m), suggesting that its influence on the state of the ionosphere and the equatorial anomaly is negligible. Therefore, the hypothesis proposed by Pulinets (2009) is not justifiable from a physical point of view and cannot serve as a basis for a model of lithosphere-ionosphere coupling.

For the same reason, the assumption laid out in the aforementioned work contradicts the numerical modeling results obtained by Zolotov et al. (2008), Klimenko et al. (2011, 2012), and Namgaladze et al. (2009). These researchers showed that the observed

TEC perturbations were associated with a rise of the ionospheric electric field of seismic origin to values of 3–9 mV/m. Nevertheless, the hypothesis of Pulinets (2009) that did not correspond to the numerical modeling results was used by Klimenko et al. (2012), although this hypothesis provided an ionospheric electric field three or four orders of magnitude weaker than that required to explain the numerical modeling results. In his work (2012), Pulinets also discusses a possible mechanism of the TEC formation mechanism in the low-latitude ionosphere, which was presented by Klimenko et al. (2012). A model of electric field generation that forms a basis for this mechanism contradicts the experimental data. While discussing other possible explanations of the experimental data, Pulinets (2012) revealed that he did not have a clear understanding of the difference between the conduction current and the extraneous current due to the EMF. The fair-weather current density is $\sim 10^{-12}$ A/m^2, while the extraneous current can appreciably exceed this value since it is related to a force field of non-electric nature. The extraneous current is determined via well known measured atmospheric characteristics. Moreover, it is the total current, which is a sum of the conduction current and extraneous current, that is constant over height rather than the conduction current alone. This misunderstanding seems to be a reason why Pulinets (2012) constructed the physically inadequate model of the field penetration into the ionosphere. Therefore, the question of how the lithospheric processes can lead to a TEC perturbation remains unanswered in the aforementioned works.

It is well to bear in mind that the plasma drift in the F region is not the only consequence of the appearance of ionospheric electric field. As was shown by Sorokin and Chmyrev (1999), the enhancement of the electric field and the related amount of the heat that released in the E layer of the ionosphere as a result of the ionospheric electric current leads to a rise in the temperature of the F region. This affects the processes that form the F region. The heat flux q that is radiated by a thin conductive layer with the integrated conductivity Σ in a horizontal electric field with the strength E is equal to $q = \Sigma E^2$ by an order of magnitude. Assuming that Σ = 3–30 mho/m and E = 6 mV/m, we obtain $q = (10^{-4}–10^{-3})$ W/m^2. The short wavelength radiation from the Sun ($\lambda < 0.1026$ μm) is one of the main sources that heat up the ionosphere. The heat afflux due to the absorption of this radiation at heights above 100 km is $\sim q = 10^{-3}$ W/m^2 and can vary by a factor of a few to become either stronger or weaker. These estimates suggest that the heat released due to the electric current in the ionosphere over an earthquake preparation zone is a substantial part of the overall heat balance in the ionosphere. Hence, this heat source decisively affects the state of the ionosphere. The heating due to ionospheric currents increases the scales of height distributions of the ionospheric components and, correspondingly, the height profile of the $F2$ layer. Since the heat source is localized in the lower ionospheric layers (120–150 km), the heating-up of the upper ionospheric layers that are located above the current layer is due to the motion of the heated gas that moves vertically upward. Preliminary estimates indicate that the heating-up of the ionosphere that occurs upon arising an electric field of E = 6 mV/m results in a relative TEC variation by dozens of percent. Hence, the TEC variations due to the heating of the ionosphere and the plasma drift in this field are on the same order of magnitude. The spatial TEC distribution arises as a result of the action of these two factors, with the TEC behavior depending on the relationship between them.

2. RESULTS OF THE TEC PERTURBATION MONITORING OVER A SEISMIC REGION

The dynamics of the TEC behavior and its spatial distribution display the current state of the ionosphere and its anomalies. Anomalies of the ionospheric characteristics of seismic origin that have been actively discussed lately are an outcome of a number of processes associated with lithosphere-atmosphere-ionosphere (LAI) interactions. An extra electric field **E** that arises in the ionosphere over a future earthquake preparation zone is considered to be the main source of these ionospheric anomalies. The plasma transfer due to this extra field in the direction of $\mathbf{E} \times \mathbf{B}$ drift should (or can) produce regions with both reduced (outflow of plasma) and enhanced (accumulation of plasma) TEC.

The earthquake that occurred in China on May 12, 2008 was the most informative one for stimulating numerous analyses of the seismic-origin TEC anomalies. In the first place, a dense domestic network of Chinese GPS receivers and ionoprobes turned out to be very useful. Maps of the TEC distribution with detailed spatial and temporal resolutions (1 h) were obtained; the global TEC maps of the IGS network (IONEX format) that are generally used by researchers in their publications (5° in longitude and 2.5° in latitude) cannot normally reach such resolutions. A sequence of Chinese image maps presents the detailed development of a positive TEC anomaly to the southeast of the epicenter (Zhao et al., 2008, 2010). The anomaly began to develop after 0300 PM local time and reached the maximum between 0600–0700 PM. According to the IGS IONEX data, similar images of this anomaly were obtained by many researchers (for 0600–0800 PM) (see, e.g., Zhao et al., 2010; Klimenko et al., 2011). Note that only the maps based on the IGS data show a weak and less pronounced (developed) anomaly in the southern hemisphere.

Figure 1 presents such an image that we obtained using the IGS data. The projection of a magnetic meridian is plotted. It can be seen that the TEC anomaly spot in the southern hemisphere is not a projection

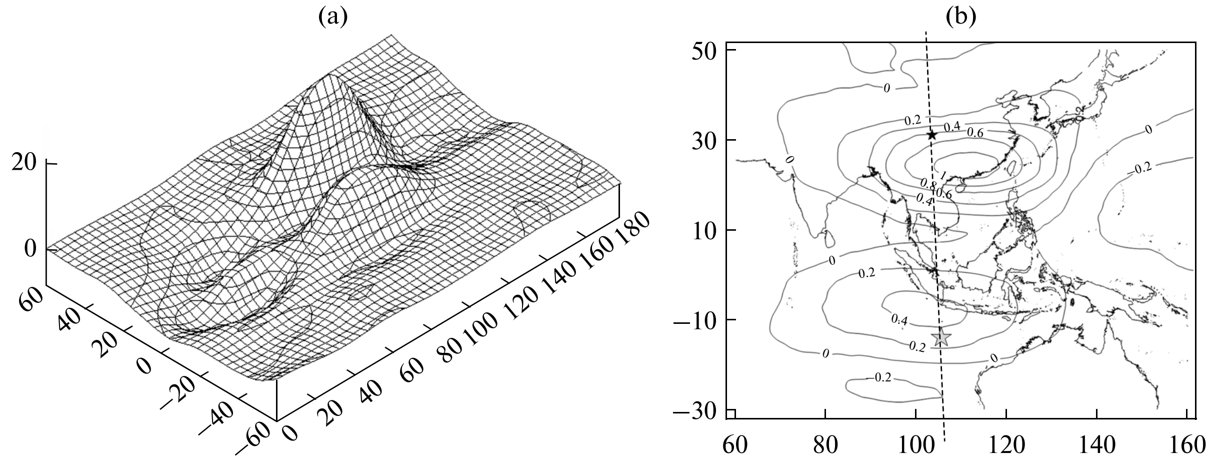

Fig. 1. Differential TEC maps of the Chinese earthquake (May 12, 2008). (a) The TEC anomaly in absolute units (TECU); (b) the TEC anomaly in relative units. The dashed line is a projection of the magnetic meridian. The epicenter location and its magnetic conjugate point in the southern hemisphere are denoted by the asterisks.

of the main spot (near the epicenter) along the geomagnetic field lines. The main physical prerequisites suggest that the extra electric field should be transferred to the magnetically conjugate hemisphere without being distorted, owing to high longitudinal conductivity. The resulting drift should produce this plasma redistribution both over the earthquake preparation zone and in the magnetically conjugate ionosphere. Note that along with the absence of the expected symmetry of the TEC anomaly location relative to the magnetic equator, it can be seen in Fig. 1 that the "centroids" of the anomalies in the two hemispheres are on different sides of the magnetic meridian that passes through the earthquake epicenter (to the east of this on the north and to the west on the south). A negative part of the anomaly was not detected; nor was it detected in the previous investigations. This suggests that the current models and ideas concerning the ionosphere response to the earthquake preparation in the form of a TEC anomaly due to plasma drift in an electric field are not adequate and cannot represent the real situation correctly.

We emphasize that this earthquake in China with the TEC anomalies was most informative (Chinese GPS and ionoprobe network, IGS IONEX maps, *DEMETER* satellite), stimulating many publications attempting to model the phenomenon. The discussion of the data obtained during this earthquake reflects the modern understanding of LAI processes on the eve of earthquakes. It is worth mentioning that the current models cannot answer the questions of why the negative (positive) anomaly is absent and, above all, why the asymmetry of the effect arises in magnetically conjugate regions and how its location relative to the geomagnetic meridian can be explained. It is obvious that additional processes should be involved in a model to adequately describe these peculiarities in TEC variations on the eve of earthquakes.

3. PERTURBATION OF THE GLOBAL CURRENT SYSTEM IN A SEISMOACTIVE REGION

Below, we consider a mechanism of the influence of seismic processes on the ionosphere that can be used to explain the results of the TEC observation. The electrodynamic model of the atmosphere-ionosphere coupling forms the basis for this mechanism (Sorokin and Chmyrev, 2002; Sorokin et al., 2001; Sorokin et al., 2005a; Sorokin et al., 2007; Sorokin and Chmyrev, 2010; and references therein). It is this model that provided the first explanation of observational results obtained for the quasistatic electric field perturbation in the ionosphere that reached 10 mV/m; furthermore, the model could explain the absence of the field perturbation at the Earth's surface in the seismoactive region, which other models failed to explain. According to this model, an increase of the electric field in the ionosphere is due to the EMF formation and the variation in the electrophysical characteristics of the lower atmosphere due to intense ejections of soil gases, aerosols, and radioactive substances from the focus of the earthquake in the stage of its preparation. The inclusion of the EMF in the global atmosphere-ionosphere electric circuit leads to the perturbation of the conduction current in this circuit. The perturbation of the electric current in the global circuit over the seismoactive region results in an appreciable modification of the *F* region in the ionosphere. In the model, a theory of the quasistatic electric field generation in the atmosphere-ionosphere system and methods of its spatial distribution are developed, and theoretical studies of the mechanisms of the EMF formation in the lower atmosphere are carried out as well. The spatial distribution of the aerosol concentration near the Earth's surface is an input parameter of the theory.

Let us make use of the results taken from the aforementioned works to estimate the horizontal distribution of the ionospheric electric field. For these calculations, we will use the Cartesian coordinate system (x, y, z) with the z axis directed vertically upward. The origin of the coordinates is located on the Earth's surface, where the x axis is directed along the magnetic meridian and the y axis is directed eastward. The conductive layer of the lower ionosphere is located at the height $z = z_1$. The spatial distribution of the horizontal components of the electric field perturbation $\mathbf{E}_1$ related to the emergence of an extra current in the global circuit upon including an EMF into this circuit is determined by the potential φ:

$$E_{1x} = -\partial\varphi/\partial x; \quad E_{1y} = -\partial\varphi/\partial y.$$

Since the longitudinal component of the ionospheric conductivity appreciably exceeds its transverse components, the potential distribution in the horizontal plane $\varphi_1(x, y)$ at the lower ionospheric boundary $z = z_1$ is transferred without variations along the geomagnetic lines of force and is determined at an arbitrary height $z > z_1$ by the expression:

$$\varphi(x, y, z) = \varphi_1\left(x - \frac{z - z_1}{\mathrm{tg} I}, y\right).$$

The $\varphi_1(x, y)$ potential is derived from the equation (Sorokin et al., 2005b):

$$\frac{1}{\sin^2 I}\frac{\partial^2\varphi_1}{\partial x^2} + \frac{\partial^2\varphi_1}{\partial y^2} = -\frac{j_a(x, y)}{2\Sigma_P}, \quad (1)$$

where $j_a(x, y)$ is the horizontal density distribution of the conduction current (that flows from the atmosphere) at the lower boundary of the ionosphere, Σ_P is the integrated Pedersen conductivity of the ionosphere, and I is the magnetic declination angle. The extraneous EMF current in the atmospheric surface layer $j_e = j_p - j_n$ is formed by the currents of positively charged j_p and negatively charged j_n aerosols. As was shown by Sorokin et al. (2005b), the $j_a(x, y)$ current is related to these currents via the relationship

$$j_a(x, y) = \frac{1}{\rho}\left[j_p(x, y, z = 0)k_p - j_n(x, y, z = 0)k_n\right];$$
$$k_{p,n} = \int_0^{z_1} dz\frac{s_{p,n}(z)}{\sigma(z)}; \quad \rho = \int_0^{z_1}\frac{dz}{\sigma(z)}, \quad (2)$$

where $j_p(x, y, z = 0)$, and $j_n(x, y, z = 0)$ are the spatial current distributions at the Earth's surface, $s_{p,n}(z)$ are their height dependences, and $\sigma(z)$ is the atmospheric conductivity.

The mechanism of the extraneous EMF current formation due to the dynamics of charged aerosols in the atmospheric surface layers was considered in (Sorokin and Yashchenko, 1999, 2000; Sorokin and Yaschenko, 2000; Sorokin et al., 2007). The EMF can arise as a result of the intensification of the charged soil aerosol ejection from the lithosphere to the atmosphere or a change in meteorological conditions if the height distribution of these aerosols is stable. A quasistatic height distribution of aerosols can form as a result of their turbulent transport upward and gravitational settling. The turbulent transport occurs because of the vertical gradient of the horizontal wind as the kinetic wind energy is transformed into the energy of turbulent pulsations and also because of the thermal instability of the atmosphere when the negative temperature gradient exceeds its adiabatic gradient. The aerosols are conveyed by turbulent vortices from height regions where their concentration is high to those where the aerosol concentration is low. The balance is reached when the vertical aerosol flux is compensated by the gravitational settling of aerosols. The calculations carried out in the above cited works indicate that the extraneous current decreases with height and its value varies within $\sim 10^{-8}$–10^{-6} A/m^2 in the atmospheric surface layer. To estimate the value of the field, the height distributions of the atmospheric conductivity and the extraneous current are approximated by the exponents:

$$\sigma(z) = \sigma_0\exp(z/h);$$
$$s_p(z) = \exp(-z/h_p); \quad s_n(z) = \exp(-z/h_n), \quad (3)$$

where h, h_p, and h_n are the scales of the corresponding height distributions and σ_0 is the atmospheric conductivity near the Earth's surface. The law of conservation of electric current yields the following expression for the vertical component of perturbation of the electric field E_{1z} in the Earth–ionosphere layer:

$$\sigma(z)E_{1z}(x, y, z) = j_a(x, y) - j_e(x, y, z).$$

Using formulas (1) and (2), we obtain

$$\sigma_0 E_{1z}(x, y, 0) = j_a(x, y) - j_p(x, y, 0) + j_n(x, y, 0),$$
$$\rho j_a(x, y) = j_p(x, y, 0)k_p - j_n(x, y, 0)k_n, \quad (4)$$
$$\rho = h/\sigma_0; \quad k_{p,n} = hh_{p,n}/\sigma_0(h + h_{p,n}).$$

The j_p and j_n currents of positively and negatively charged aerosols are not independent. These form in the presence of the feedback between the extraneous EMF current and the vertical component of perturbation of the electric field at the Earth's surface (Sorokin et al., 2005). The feedback arises as a result of the potential barrier that exists at the surface of a conducting Earth for the charged aerosols that traverse this surface as they are conveyed by soil gases into the atmosphere. A consequence of this is the fact that a value of the electric field perturbation is bounded at the Earth's surface. The calculations indicate that this value does not exceed the background field (Sorokin et al., 2005). In other words, there is no appreciable perturbation of the quasistatic field in a seismoactive region, which is confirmed by the observational results. Hence, to estimate the field in equality (4), we can assume for simplicity that $E_{1z}(0) = 0$. This equality yields the simple relationships between the conduction current at the lower ionospheric boundary and the extraneous current at the Earth's surface:

$$j_a(z_1)/j_p(0) = (h_p - h_n)/(h + h_p);\quad j_n(0)/j_p(0) = (h + h_n)/(h + h_p). \tag{5}$$

The distribution of aerosol particles as a function of electric charge and height was obtained by Sorokin et al. (2001). This function has a sense of probability that a particle has the charge Ze at the height z at the point in time t. Sorokin et al. (2001) derived an equation for the vertical component of the extraneous EMF current density with the given atmospheric conductivity, turbulent diffusion coefficient, and rate of gravitational aerosol settling using the moments of the distribution function. This equation allows the determination of the height distribution of the extraneous current. It is assumed that the aerosol charge is fixed and there is no radioactivity in the atmosphere. The equation suggests that the extraneous current $j_e(0,t)$ near the Earth's surface can be estimated as

$$j_p(x,y,0) = (Ze\sigma_0/\varepsilon_0)\,h_p N_p(x,y,0);\quad j_n(x,y,0) = (Ze\sigma_0/\varepsilon_0)\,h_n N_n(x,y,0), \tag{6}$$

where e is the elementary charge, ε_0 is the electric constant, Z is the number of elementary charges on aerosols, and $N_{p,n}$ are the concentrations of positively and negatively charged aerosols. Equalities (5) and (6) yield the relationship between the atmospheric electric current density at the lower ionospheric boundary and the concentration of positively charged aerosols at the Earth's surface:

$$j_a = \frac{Ze\sigma_0 h_p(h_p - h_n)}{\varepsilon_0(h + h_p)} N_p. \tag{7}$$

Substituting (7) into (1) gives an equation for calculating the horizontal distribution of the electric field potential in the ionosphere depending on the horizontal distribution of aerosol concentration at the Earth's surface for different magnetic declinations:

$$\frac{1}{\sin^2 I}\frac{\partial^2\varphi_1(x,y)}{\partial x^2} + \frac{\partial^2\varphi_1(x,y)}{\partial y^2} = -\frac{Ze\sigma_0 h_p(h_p - h_n)}{2\varepsilon_0\Sigma_P(h + h_p)} N_p(x,y). \tag{8}$$

For our calculations, we choose a spatial distribution of the aerosol concentration at the Earth's surface in the following form:

$$N_p(x,y) = N_{p0}\exp\left(-\frac{x^2}{l_x^2} - \frac{y^2}{l_y^2}\right).$$

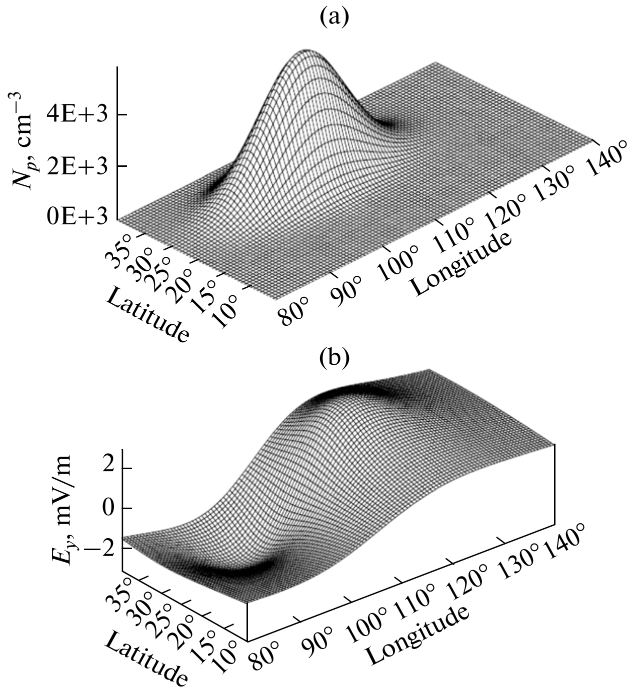

Fig. 2. (a) Spatial distribution of the positively charged aerosol concentration at the Earth's surface. (b) The horizontal distribution of the electric-field zonal component in the ionosphere.

Figure 2a displays the spatial aerosol distribution obtained using this formula for $N_{p0} = 5 \times 10^9$ m^{-3}, $l_x =$ 500 km, and $l_y =$ 1200 km. The spatial aerosol distribution (Fig. 2a) was used to calculate the spatial distribution of the zonal component of the ionospheric electric field perturbation using formula (8). The aerosol ejection epicenter (the point $x = y = 0$) was chosen at the point with coordinates (30° N; 105° E). The TEC perturbation focus is located at the point with coordinates (25° N; 115° E). The calculation results are given in Fig. 2b. The following parameter values were chosen: $\sigma_0 = 2 \times 10^{-14}$ mho/m, $\Sigma_p = 6$ mho, $e = 1.6 \times 10^{-19}$ C, $\varepsilon_0 = 8.8 \times 10^{-12}$ F/m, $Z = 100$, $h_p = 5$ km, $h_n = 2$ km, $h = 3$ km, $I = 37°$. For these parameter values, the maximum conduction current at the lower boundary of the ionosphere (7) was $j_a = 3.3 \times 10^{-7}$ A/m^2. The graph suggests that the electric field perturbation in the ionosphere reaches a value of (4–5) mV/m. This field corresponds to the numeric modeling results obtained in the aforementioned works. Hence, the considered model of lithosphere-ionosphere coupling can be used to study the nature of TEC perturbation in the periods of enhanced seismic activity.

4. ESTIMATION OF THE SPATIAL TEC DISTRIBUTION CHARACTERISTICS

Let us consider a modification of the spatial distribution of the ionospheric electron concentration N due to a perturbation of the global electric current circuit in a seismic region. The TEC perturbation is determined by the plasma concentration in the $F2$ ionospheric layer in the height range from 200 to 1000 km. According to Bryunelli and Namgaladze (1988), it is sufficient to take into account only the vertical transport of charged particles in the middle-latitude ionosphere when calculating the TEC since the horizontal derivatives of macroscopic parameters are small. Observational results suggest that the horizontal scale of the ionospheric perturbation is ~1000 km, which appreciably exceeds the vertical scale of the electron concentration variation.

Let us estimate the TEC perturbation in an isothermal atmosphere due to the vertical $F2$-layer plasma drift in the electric field and the ionospheric heating by this field. The electron concentration $N(z)$ will be determined using the stationary transport equation (Bryunelli and Namgaladze, 1988):

$$\frac{dJ(z)}{dz} = q(z) - \beta(z)N(z);$$
$$J(z) = -D(z)\left[\frac{dN}{dz} + \frac{N}{2H}\right] + wN, \qquad (9)$$

where $q(z)$ is the ionization rate; $\beta(z)$ is the effective recombination coefficient; $D(z) = k_BT/M\nu_{in}$ is the ambipolar diffusion coefficient, $H = k_BT/Mg$ is the height of the homogeneous atmosphere, k_B is the Boltzmann constant, T is the atmospheric temperature, M is the mass of an ion and a molecule, ν_{in} is the frequency of collisions between ions and molecules, and g is the free fall acceleration. The vertical plasma drift velocity w due to the electric field $\mathbf{E}$ and the neutral wind with the velocity $\mathbf{V}$ is determined using the formula

$$w = (E_y/B)\cos I + V_x \cos I \sin I,$$

where E_y and V_x are the electric field and horizontal wind components, respectively, and B is the geomagnetic field induction. The electric field E_y is a sum of its unperturbed value E_{0y} and the perturbation E_{1y} that arises in the ionosphere due to the EMF inclusion into the global circuit: $E_y = E_{0y} + E_{1y}$. Substituting this sum into the last equation yields

$$w = w_0 + \frac{E_{y1}}{B}\cos I; \quad w_0 = \frac{E_{y0}}{B}\cos I + V_x \cos I \sin I, \qquad (10)$$

where w_0 is the unperturbed drift velocity due to the electric field and the wind of non-seismic origin. The height dependence of the ionization rate $q(z)$ can be represented by the Chapman function. Above its maximum $z \approx z_0$, this function is approximately proportional to the density of the neutral gas, namely, the atomic oxygen:

$$q(z) = q_0 \exp\left(-\frac{z - z_0}{H}\right).$$

Let us use the following designations: T_0 for the temperature of the ionosphere in the absence of its heating by the current of seismic origin, $H_0 = k_BT_0/Mg$ for the height of the homogeneous atmosphere that corresponds to the temperature T_0, and $\tau = T/T_0$ for the relative temperature variation. The ionization rate as a function of temperature is then written in the form

$$q(z) = q_0 \exp\left(-\frac{z - z_0}{H_0\tau}\right). \qquad (11)$$

The maximum ionization rate q_0 varies within (10^8–10^9) m^{-3} s^{-3}, depending on the time of day and the solar activity.

The integration of Eq. (9) over z between z_0 and ∞, where $z_0 \approx 200$ km is the lower boundary of the $F2$ layer, yields

$$J_\infty - J(z_0) = Q - \bar{\beta} U; \quad Q = \int_{z_0}^{\infty} q(z)dz = q_0 H_0 \tau, \qquad (12)$$

where $J(z_0)$ is the ion flux at the lower boundary of the ionospheric $F2$ layer, J_∞ is the ion flux at the upper ionospheric boundary, and $\bar{\beta} = \int_{z_0}^{\infty} \beta(z)N(z)dz \Big/ U$ is the average recombination coefficient. In equality (12), U stands for the TEC that is determined using the formula

$$U = \int_{z_0}^{\infty} N(z)dz. \qquad (13)$$

To estimate the ion flux $J(z_0)$ at the lower boundary of the $F2$ layer, we neglect the effects of ion diffusion and only take into account the ion drift:

$$J(z_0) \approx wN(z_0) = wN_0.$$

Expression (12) gives the desired TEC value:

$$U = \frac{q_0 H_0 \tau + wN_0 - J_\infty}{\bar{\beta}}. \qquad (14)$$

The weighted average recombination coefficient $\bar{\beta}$ is determined via equating the TEC value that is calculated using (14) in the absence of electric field perturbation by a seismic source and its U_0 value derived from formula (13) using the IRI-2007 ionosphere model:

$$U_0 = \frac{q_0 H_0 + w_0 N_0 - J_\infty}{\bar{\beta}}. \qquad (15)$$

We will search for the TEC perturbation related to the generation of an extra electric field E_{1y} in the ionosphere $\Delta U = U - U_0$, relative to its unperturbed value U_0. Using formula (10) for the drift velocity perturbation due to an extra electric field, we obtain

$$\frac{\Delta U}{U_0} = \frac{q_0 H_0(\tau - 1) + \left(E_{1y}/B\right) N_0 \cos I}{q_0 H_0 + w_0 N_0 - J_\infty}. \quad (16)$$

Sorokin and Chmyrev (1999) considered a model of the ionospheric heating due to the convective transfer of the heat that is released while the electric current flows in the conductive layer of the lower ionosphere. The relative ionospheric temperature τ depends on the ionospheric electric field as follows:

$$\tau\left(\sqrt{\tau} - 1\right) = \lambda/\lambda^*; \quad \lambda^* = 2\kappa_0 T_0/z_1, \quad (17)$$

where κ_0 is the coefficient of heat conductivity in the atmosphere with the temperature T_0. In equality (17), λ stands for the surface density of the heat output due to the electric current that flows in the conductive layer of the lower ionosphere:

$$\lambda = \Sigma_P\left(E_x^2/\sin^2 I + E_y^2\right) = \\ = \Sigma_P\left[\frac{1}{\sin^2 I}\left(\frac{\partial\varphi_1}{\partial x}\right)^2 + \left(\frac{\partial\varphi_1}{\partial y}\right)^2\right], \quad (18)$$

Figure 3a presents the calculation results of the horizontal λ distribution obtained using formulas (8) and (18). The heat output in the E region brings about the heating of the F ionospheric region and increase of its temperature. The ionospheric horizontal temperature distribution emerging due to the heating of the ionosphere by the electric field of the current that is generated in the global circuit as a result of the aerosol injection into the atmosphere is calculated using (17) and is displayed in Fig. 3b. The calculation was performed using the following values: $\lambda^* \sim 2 \times 10^{-4}$ W/m^2 and $\Sigma_p = 6$ mho.

The plasma drift in the electric field is accompanied by TEC increases and decreases in perturbed regions. The chart of TEC perturbation formation in this case is presented in Fig. 4. This diagram suggests that the plasma drift is directed upward in the region where the field is directed eastward. Otherwise, the plasma drift is directed downward in the region where the field is directed westward. The calculation results given above indicate that the field exceeds its background value in the ionosphere by a factor of a few. Hence, the plasma drift in this field leads to an appreciable TEC variation. The diagram of TEC perturbation formation due to the heating of the ionosphere by the current that flows in its conductive layer is given in Fig. 5. The ionospheric temperature increases over the heat output region, resulting in an extension of the ionospheric component vertical distribution scale. This modification of the height ionospheric profile leads to TEC growth in the whole perturbed region.

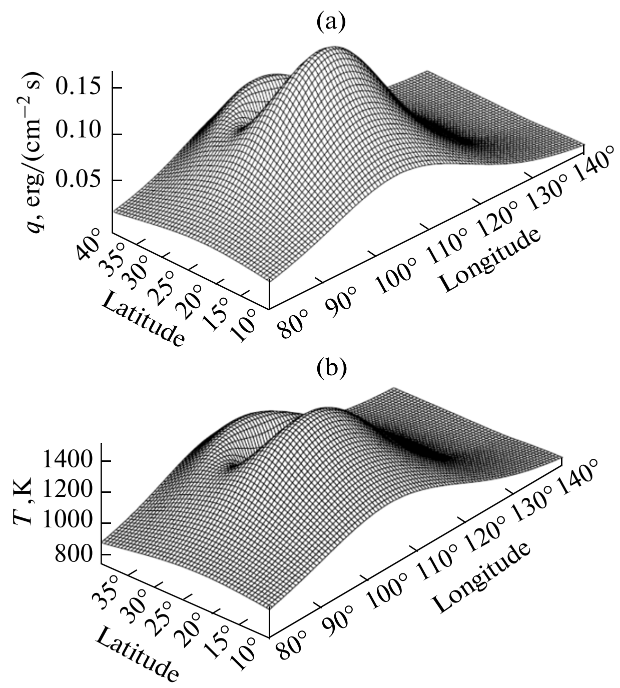

Fig. 3. (a) The horizontal distribution of the heat output surface density due to the electric current flowing in the conductive layer of the lower ionosphere. (b) The horizontal distribution of the temperature in the ionosphere heated by the electric current.

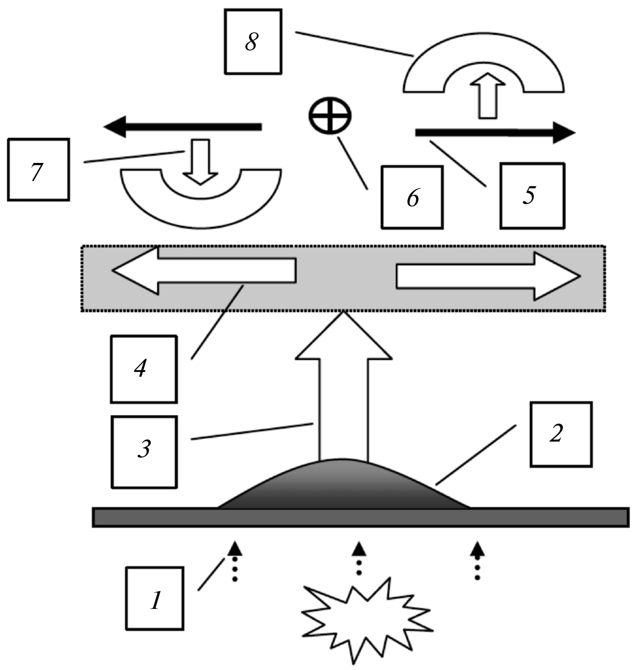

Fig. 4. The scheme for the TEC perturbation formation due to the plasma drift in the electric field: (*1*) the injection of aerosols by the soil gas; (*2*) the EMF generation region in the atmospheric surface layer; (*3*) the conduction current in the atmosphere; (*4*) the electric current in the ionospheric conductive layer; (*5*) the electric current in the ionosphere; (*6*) the geomagnetic field; (*7*) the plasma drift velocity; (*8*) the TEC perturbation.

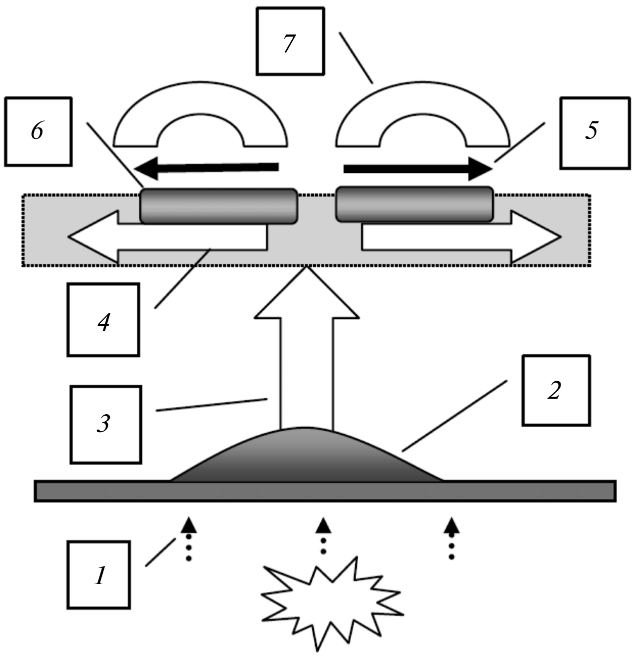

Fig. 5. The scheme for the TEC-perturbation formation due to the plasma drift in the electric field: (*1*) the injection of aerosols by the soil gas; (*2*) the EMF generation region in the atmospheric surface layer; (*3*) the conduction current in the atmosphere; (*4*) the electric current in the ionospheric conductive layer; (*5*) the electric current in the ionosphere; (*6*) the region of the heat output due to the current in the ionosphere; (*7*) the TEC perturbation.

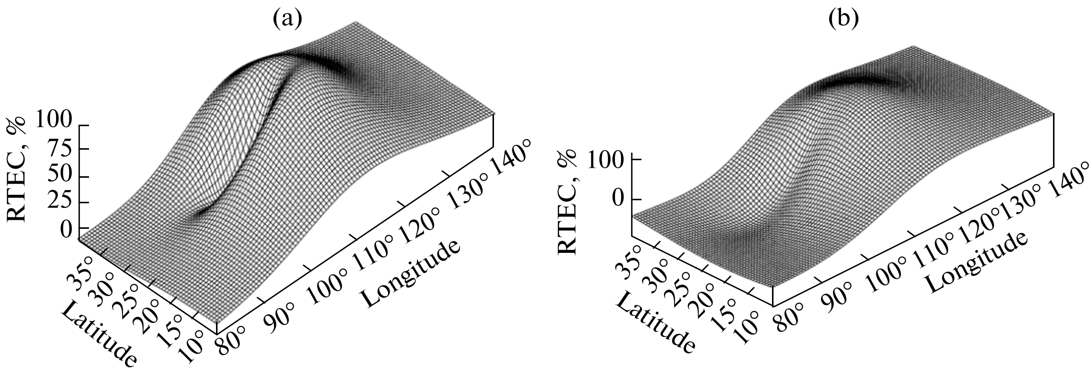

Fig. 6. Spatial distribution of the relative TEC perturbation for (a) the maximum in solar activity; (b) the minimum in solar activity.

The spatial TEC distribution arises as a result of the joint action of these two factors, with its behavior depending on the relationship between these factors. The spatial distribution of the TEC perturbation that arises as a result of the joint action of the vertical plasma drift in the electric field of the *F*-region and the heating of the ionosphere by this field is calculated using formulas (10), (16), (17), and (18). Figs. 6a and 6b present the results of the relative TEC perturbation calculated for different solar-activity levels with the following values of parameters: $N_0 = 3 \times 10^{11}$ m^{-3}, $E_{0y} = 1.5$ mV/m, $V_x = 9$ m/s, $B = 5 \times 10^{-5}$ T, and $H_0 =$ 10 km. The graph in Fig. 6a is obtained for an ionization rate of $q_0 = 5 \times 10^8$ m^{-3} s^{-1} at the lower *F*2-layer boundary that corresponds to an enhanced level of solar activity. To calculate the graph in Fig. 6b, a value of $q_0 = 10^8$ m^{-3} s^{-1} that corresponds to a low level of solar activity is used. An ion flux of approximately $J_\infty \sim 10^{12}$ m^{-2} s^{-1} is directed upward at the upper boundary of the daytime ionosphere (Evans, 1975). An analogous flux is directed downward in the nighttime.

CONCLUSIONS

The strengthening of seismic activity leads to an electric field increase that is detected in the ionosphere over an earthquake epicenter several days before the main shock. An ionospheric perturbation that is detected as a variation in the total electron content can be generated in the same region. Observations suggest that the TEC can either grow or diminish (or both) in the perturbed region. The numerical modeling indicates that the detected TEC variations are possible if the electric field in the ionosphere reaches a value of (1–10) mV/m in the earthquake preparation stage. In the process, there are no any appreciable variations of the electric field vertical component at the Earth's surface in the seismoactive region during the period of the TEC perturbation formation in the ionosphere. These electric field variations in the atmosphere-ionosphere system are only possible as a result of the electric field perturbation in the global circuit upon the injection of charged aerosols of the soil gases into the atmosphere. An EMF forms as a result of the turbulent and convective transfer and the gravitational settling of these aerosols in the atmospheric surface layer; the inclusion of this EMF in the global circuit brings about the perturbation of the conduction current in this circuit. The EMF generation triggers a mechanism of the seismic activity transfer into the ionosphere. The calculations indicate that an increase in the aerosol concentration near the Earth's surface by a factor of a few leads to a relative TEC variation by dozens of percent. The emergence of the ionospheric electric field leads not only to plasma drift in the *F* region. An increase of the electric field and the related increase of the heat released in the ionospheric *E* region due to the flow of electric current results in a temperature rise in the *F* region. eating by the ionospheric currents enlarges the scales of the ionospheric component height distributions and, hence, the height profile of the *F*2 layer. This forms the spatial distribution of the like-sign TEC perturbation. The ionospheric heating due to the generation of the electric field $E \sim 6$ mV/m and the plasma drift in this field bring about equal relative TEC variations. The resulting spatial TEC distribution arises as a result of the action of these two factors and its behavior depends on the relationship between them. To explain a number of specific features in the TEC behavior on the eve of an earthquake, it is necessary to further develop the model considered above, given the additional factors that affect the formation of the spatial TEC distribution.

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