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DC electric field formation in the mid-latitude ionosphere over typhoon and earthquake regions

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Abstract

The further development of electrodynamic model of strong DC electric field formation in the ionosphere above typhoon and earthquake regions has been presented. According to this model, the external electric current works as a source of conductivity current perturbation in the atmosphere–ionosphere electric circuit. The origin of such a current is connected with upward transportation of charged water drops and aerosols in hurricane convection zone and convection of charged aerosols, which are injected in the atmosphere by elevation of soil gases in the ground of seismic region. This paper presents the method for calculation of the electric field in the atmosphere and the ionosphere generated by given distribution of external electric current in the atmosphere. Calculations of spatial distribution of DC electric field in the ionosphere were carried out with the account of oblique geomagnetic field and the conjugate ionosphere effects.

Keywords: Ionosphere; Earthquake; Typhoon; Electric field; External current; Charged aerosols; Convective transport

1. Introduction

The electrodynamic model of the atmosphere–ionosphere coupling (Sorokin et al., 2001) gives an explanation to some electromagnetic and plasma phenomena preceding typhoons and earthquakes by amplification of DC electric field in the ionosphere over disturbed region. To initiate these phenomena the electric field in the ionosphere should reach a magnitude ~10 mV/m. DC electric field exceeding 80 mV/m in magnitude were observed by Kelley et al. (1985) and Holzworth et al. (1985) in the stratosphere at the distances ~100 km from thunderstorm cells. Besides AC electric fields with amplitude above 10 mV/m and significant magnetic field-aligned component were registered in the ionosphere. It was found that the vertical electric current density exceeded 120 pA/m^2 at the altitudes 50–60 km. AC electric fields ~40 mV/m and correlated intensity bursts of upward magnetic field-aligned fluxes of 1 keV electrons were observed over hurricane Debby (Burke et al., 1992). Mikhailova et al. (2000) have presented satellite data of the ULF/VLF radiations related to typhoons development. Observations of DC electric fields with magnitude up to 20 mV/m in the upper ionosphere over the tropical cyclone zone were reported by Isaev et al. (2002a,b) and Sorokin et al. (2005b). Many of these phenomena display the properties typical for earthquake-related ionospheric disturbances. Among them are anomalous DC electric fields and ULF/ELF electromagnetic emissions (Gokhberg et al., 1982; Chmyrev et al., 1989; Bilichenko et al., 1990; Serebryakova et al., 1992; Molchanov et al., 1993; Parrot, 1994) and plasma density inhomogeneities (Chmyrev et al., 1997; Afonin et al., 1999) excited in the ionosphere prior to strong earthquakes.

The electro-physical parameters of the lower troposphere such as concentration, dimensions and mobility of charge marine aerosols and dielectric constant of air are

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correlated with the meteorological parameters – cloudiness, temperature, humidity, pressure and intensity of atmospheric convection. Perturbations in the meteorological parameters at definite phases of tropical cyclone development initiate the disturbances of electrical conductivity and vertical transport of charge aerosols and water drops that leads to formation of external electric current in the lower atmosphere. Similar external current arises as a result of convective transport of charge aerosols injected into the atmosphere at the enhancement of seismic activity. Insertion of external electric current modifies the distribution of conductivity current in global atmosphere–ionosphere electric circuit and leads to generation of DC electric field disturbances over a zone of strong atmospheric perturbation. The most important property of this mechanism is that numerous electromagnetic and plasma effects can be explained by the operation of only one source – an amplification of DC electric field in the ionosphere. This source is controlled by the dynamics of atmospheric processes through modification of electrical parameters of the lower atmosphere and seismic processes.

2. Equation for DC electric field potential

Let us consider generation of the electric field **E** by external current j_e in the Earth–ionosphere layer. We derive the equations for potential φ of the electric field disturbance $\mathbf{E} = -\nabla\varphi$ in the Cartesian coordinates (x, y, z) with the axis z directed vertically upward and with the origin located on the absolutely conductive Earth's surface. Homogeneous magnetic field **B** is assumed to be directed at the angle α to x-axis (see Fig. 1). We assume that the electric field potential on this surface equals zero. The atmospheric conductivity $\sigma(z)$ depends on z-coordinate. Electric potential is derived from the equation of continuity and the Ohm's law:

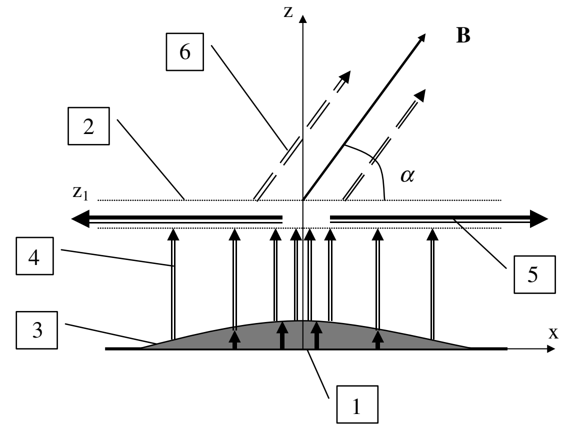

Fig. 1. Scheme of the model used for the calculations of current and field in the atmosphere–ionosphere electric circuit. (1) Earth's surface, (2) conducting ionosphere, (3) zone of upward convection of charged aerosols and external electric current formation, (4) conductivity current in the atmosphere, (5) conductivity current flowing along the ionosphere, (6) field-aligned electric current. α is the angle of magnetic field inclination.

$$\frac{\mathrm{d}}{\mathrm{d}z}\left[\sigma(z)\frac{\mathrm{d}\varphi}{\mathrm{d}z} - j_e(x,y,z)\right] = 0. \tag{1}$$

Thin conductive ionosphere is characterized by the tensor integral conductivity. In quasi-static approximation geomagnetic field lines are equipotential. Therefore, the distributions of electrical potential of the ionosphere and the field-aligned current on its upper boundary are transported into magnetically conjugate region without changes. Magnetic field-aligned electric current flowing in the magnetosphere is closed by transverse conductivity current in the conjugate ionosphere and the atmosphere. Boundary condition for potential on the ionosphere can be obtained by integrating the current continuity equation along the geomagnetic field line within the ionospheric layer (Sorokin et al., 2005b,c):

$$\begin{aligned} &\varphi|_{z=0} = 0, \\ &\sigma_1 \left.\frac{\mathrm{d}\varphi}{\mathrm{d}z}\right|_{z=z_1-0} = 2\Sigma_\mathrm{P}\left(\frac{1}{\sin^2\alpha}\frac{\partial^2\varphi_1}{\partial x^2} + \frac{\partial^2\varphi_1}{\partial y^2}\right) - \frac{\varphi_1}{\rho}, \\ &\rho = \int_0^{z_1}\frac{\mathrm{d}z}{\sigma(z)}, \end{aligned} \tag{2}$$

where $\varphi_1 = \varphi(x, y, z = z_1)$ is the electric field potential distribution in the ionosphere, $\sigma_1 = \sigma(z = z_1 - 0)$ is the conductivity of atmosphere at lower boundary of the ionosphere, Σ_P is the integral Pedersen conductivity of the ionosphere. This distribution of potential φ_1 is connected with horizontal component of the electric field and the conductivity current flowing in the ionosphere. The external current formation processes over the seismic area and the region of tropical cyclone are connected with injection of charge aerosols and vertical convective motion of gases in the lower atmosphere. These processes cover a zone with horizontal scale l of the order of hundred km. At such spatial scale equation for potential of the electric field disturbance can be approximately solved for arbitrary dependence of the atmosphere conductivity on altitude. This equation is applicable for calculation of the electric fields induced by external currents with arbitrary distribution in horizontal plane. We choose for calculations the large-scale axial symmetric spatial distribution of external current:

$$j_e(r,z) = j_{e0}\exp\left(-\frac{z}{h_j}\right)\exp\left(-\frac{x^2+y^2}{l^2}\right). \tag{3}$$

With use of (1) the boundary condition (2) yields the equation for horizontal distribution of the ionosphere potential φ_1:

$$\begin{aligned} &\frac{1}{\sin^2\alpha}\frac{\partial^2\varphi_1(x,y)}{\partial x^2} + \frac{\partial^2\varphi_1(x,y)}{\partial y^2} \\ &\quad = -\frac{j_{e0}}{2\Sigma_\mathrm{P}\rho}\exp\left(-\frac{x^2+y^2}{l^2}\right)\int_0^{z_1}\frac{\exp(-z/h_j)}{\sigma(z)}\,\mathrm{d}z. \end{aligned} \tag{4}$$

Graphs for horizontal component of the excited electric field in the ionosphere calculated by (3) and (4) at different magnetic field inclinations (α) are presented in Fig. 2.

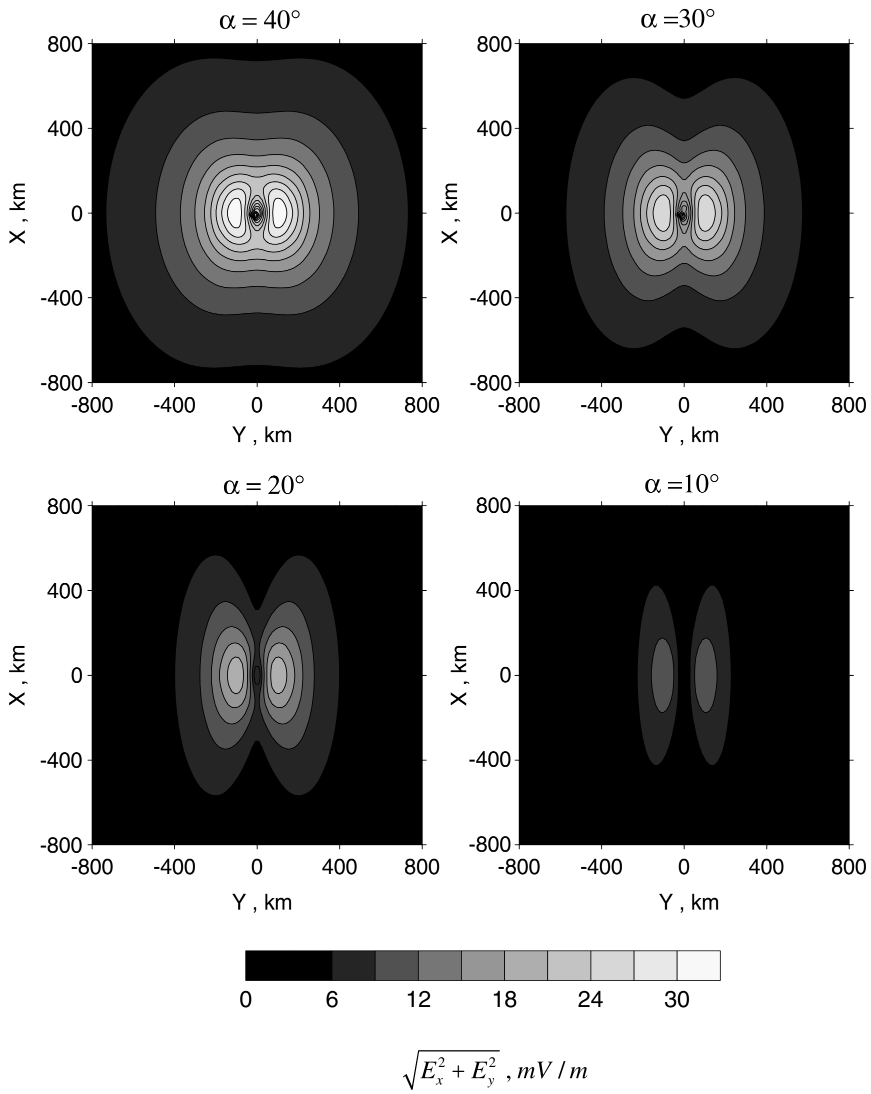

Fig. 2. Horizontal DC electric field distribution in the ionosphere over a typhoon zone calculated for different angles of magnetic field inclination α.

External current can be induced by vertical atmospheric convection acting as electrostatic generator. Upward airflow transports small positively charged particles, while downward precipitations transfer negative charge. A rate of charge separation in unitary volume of cloud is of the order of $\sim 10^{-11}$ Coulomb/m^3 s (Fleagle and Businger, 1963). Apparently, the vertical convective motion of moist atmosphere at upper altitudes in typhoon zone is characterized by lower separation rates, which are not known exactly. We assume as in Isaev et al. (2002a) that at the heights ~10 km an average charge separation rate is $\sim 4 \times 10^{-12}$ Coulomb/m^3 s for estimating of external current magnitude $j_{e0} \approx (\mathrm{d}Q/\mathrm{d}t)z_0 \approx 4 \times 10^{-6}$ A/m^2. Graphs in Fig. 2 are calculated at the following parameters:

$$l = 100\ \text{km},\quad z_0 = 10\ \text{km},\quad h = 5\ \text{km},$$

$$h_j = 10\ \text{km},\quad \Sigma_\mathrm{P} = 10^{12}\ \text{cm/s}.$$

It is seen from Fig. 2 that the electric field component lying in the plane of magnetic meridian is substantially lower than the perpendicular one. It is seen that the distribution of electric field radial component strongly depends on α. The field structure becomes two-cell (dipole-like) with very small component in the plane of meridian (in a center of hurricane) when inclination decreases below 20°.

3. DC electric field over seismic region

The quasi-stationary vertical distribution of external current may be formed as a result of a turbulent upward transfer and gravitational sedimentation of the positive and negative charged soil aerosols. The Fokker–Plank equation for the distribution function $f_i(q, z, t)$ of aerosol particles depending on the electric charge q_i, altitude and time was obtained by Sorokin et al. (2001)

$$\frac{\partial f_i}{\partial t} - w_i \frac{\partial f_i}{\partial z} - 4\pi\sigma(z) \frac{\partial}{\partial q_i}(q_i f_i) = \frac{\partial}{\partial z}\left(K_i \frac{\partial f_i}{\partial z}\right),$$

where w_i is the settling speed, K_i is the vertical eddy diffusion coefficient and index mark i has a value 'p' or 'n' correspondingly for positively and negatively charged aerosols. Spatial and temporal dependencies of aerosol number density $N_i(z,t)$, their electric charge $\rho_i(z,t)$ and current $j_i(z,t)$ densities are expressed as the moments of distribution function $f_i(q,z,t)$:

$$\begin{aligned}
N_i(z,t) &= \int_{-\infty}^{\infty} f_i(q_i,z,t)\,\mathrm{d}q_i,\\
\rho_i(z,t) &= \int_{-\infty}^{\infty} q_i f_i(q_i,z,t)\,\mathrm{d}q_i,\\
j_i(z,t) &= -w_i\int_{-\infty}^{\infty} q_i f_i(q_i,z,t)\,\mathrm{d}q_i - K_i\int_{-\infty}^{\infty} q_i\frac{\partial f_i(q_i,z,t)}{\partial z}\,\mathrm{d}q_i\\
&= -\rho_i w_i - K_i\frac{\partial\rho_i}{\partial z}.
\end{aligned}$$

Assuming that the characteristic time scale of the considered processes exceeds the relaxation time $1/4\pi\sigma$ one can find the equation for altitude distribution of external current:

$$\frac{\partial}{\partial z}\left[\frac{1}{4\pi\sigma(z)}\frac{\partial j_i(z)}{\partial z}\right] + \frac{w_i}{4\pi\sigma(z)K_i}\frac{\partial j_i(z)}{\partial z} - \frac{j_i(z)}{K_i} = 0.$$

To estimate the magnitude of external current we assume that it depends on altitude as

$$j_i(z) = j_i(0)\exp(-z/h_i),$$

where h_i is characteristic vertical scale regarding to positive (p) and negative (n) charged aerosol currents. The vertical distribution of external charge in this case is

$$\rho_i(z) = \rho_i(0)[\exp(-z/h_i) - h_i\delta(z)],$$

where $\delta(z)$ is Dirack's delta function. The external electric currents formed both positive and negative charged aerosols in the vicinity of Earth's surface are given by the equations:

$$j_{i0} = 4\pi\sigma_0 e Z_i N_{i0} h_i, \quad \rho_i(0) = eZ_i N_{i0}.$$

Ground-based measurements of the electric field variations with characteristic period exceeding 1 day at the distances <120 km from earthquake center during seismically active period show that typical magnitudes are limited by the values from tens to few hundreds V/m (Vershinin et al., 1999). Such limitation can be explained by the feedback mechanism between disturbances of vertical electric field and the causal external currents on the Earth surface (Sorokin et al., 2005a,c). These currents are formed by positive and negative charged aerosols:

$$\begin{aligned}
&j_\mathrm{e}(r,z) = j_\mathrm{p}(r)s_\mathrm{p}(z) - j_\mathrm{n}(r)s_\mathrm{n}(z),\\
&s_\mathrm{p}(z=0) = s_\mathrm{n}(z=0) = 1.
\end{aligned} \tag{5}$$

The feedback is caused by the formation of potential barrier on the ground-atmosphere boundary at the passage of upward moving charged aerosols through this boundary. Their movement upward is performed due to viscosity of soil gases flowing into the atmosphere. If for example positively charged particle goes from ground to the atmosphere, the Earth surface is charged negatively. The excited downward electric field prevents particle penetration through the surface. Generated downward electric field prevents particle penetration through the surface (see Fig. 3 for illustration). At the same time, this field stimulates the going out on the surface of the negatively charged particles. In the presence of such a coupling the magnitudes of external currents on the Earth surface depend on vertical component of the electric field on this surface:

$$\begin{aligned}
&j_\mathrm{p}(r,E_{z0}(r)) = j_{\mathrm{p}0}(r)f(E_{z0}(r)/E_{\mathrm{cp}}),\\
&j_\mathrm{n}(r,E_{z0}(r)) = j_{\mathrm{n}0}(r)f(-E_{z0}(r)/E_{\mathrm{cn}}),
\end{aligned} \tag{6}$$

where $j_{\mathrm{p}0}$ and $j_{\mathrm{n}0}$ are determined by the injection intensity of aerosols in missing of the electric field influence. For simplicity, we will assume that the aerosols of opposite signs consist of the same particles. When the negative electric field reaches the critical value, it stops the current of positive particles, while the positive electric field stops negative particles current. Qualitatively the function $f(E_{z0}/E_\mathrm{c})$ characterizing the electric field effect could be presented in a form $f=\sqrt{1+E_{z0}/E_\mathrm{c}}$. Critical field can be estimated from the balance between viscosity, gravity and electrostatic forces. The viscosity force connected with elevated soil gases acts in upward direction. The gravity force is directed downward. The electrostatic force connected with going out of positive particle is directed downward:

$$E_\mathrm{c} = (6\pi\eta RV - mg)/eZ,$$

where η is the air viscosity coefficient, V is the velocity of elevation of soil gases within ground, R is the radius of aerosol particles, $m=(4/3)\pi R^3\mu$ is the particle mass, μ is their number density. Assuming $\eta = 1.72\times10^{-4}$ g/cm s, $V=0.01$ cm/s, $R=5\times10^{-5}$ cm, $\mu=1.5$ g/cm^3, $Z=100$ we obtain $E_\mathrm{c}=0.015$ cgse $=450$ V/m, $\sigma_0 E_\mathrm{c}=10$ pA/m^2.

We obtain altitudinal distribution of the vertical component of electric field from Eq. (1):

$$E_z(r,z) = \frac{1}{\sigma(z)}\left[\frac{1}{\rho}\int_0^{z_1}\frac{j_\mathrm{e}(r,z)}{\sigma(z)} - j_\mathrm{e}(r,z)\right]. \tag{7}$$

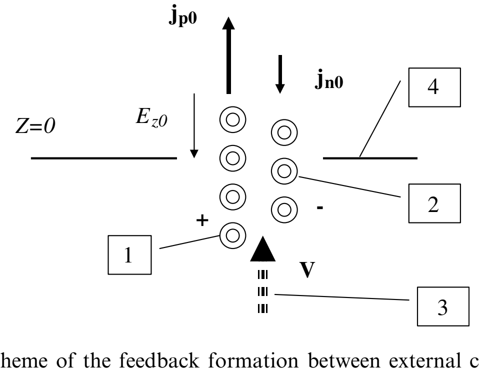

Fig. 3. Scheme of the feedback formation between external current and vertical electric field on the Earth surface. (1) Positive charged aerosols, (2) negative charged aerosols, (3) elevated soil gases, (4) the Earth surface.

Eqs. (5) and (7) give the relationship between electric field and external current on the Earth's surface:

$$\begin{aligned}
&E_{z0}(r) = \frac{1}{\sigma_0}\left[j_{\mathrm{p}}(r)\left(\frac{k_{\mathrm{p}}}{\rho}-1\right) - j_{\mathrm{n}}(r)\left(\frac{k_{\mathrm{n}}}{\rho}-1\right)\right],\\
&k_{\mathrm{p,n}} = \int_0^{z_1} \mathrm{d}z \frac{s_{\mathrm{p,n}}(z)}{\sigma(z)},\\
&E_{z0}(r) = E_z(r, z=0),\\
&\sigma_0 = \sigma(z=0).
\end{aligned} \tag{8}$$

Eqs. (6) and (7) give the relationship between electric field and external current on the Earth's surface with accounting feedback mechanism mentioned above:

$$\begin{aligned}
E_{z0}(r) = \frac{1}{\sigma_0}\Bigg[&j_{\mathrm{p}0}(r)\left(\frac{k_{\mathrm{p}}}{\rho}-1\right)\sqrt{1+\frac{E_{z0}(r)}{E_{\mathrm{c}}}}\\
&- j_{\mathrm{n}0}(r)\left(\frac{k_{\mathrm{n}}}{\rho}-1\right)\sqrt{1-\frac{E_{z0}(r)}{E_{\mathrm{c}}}}\Bigg].
\end{aligned} \tag{9}$$

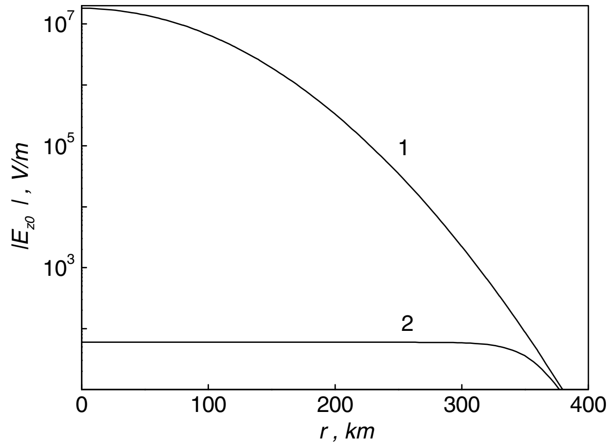

Fig. 4. Example of calculation of the vertical component of electric field on the Earth's surface for axially symmetric distribution of the external electric current. (1) Dependence of electric current on horizontal distance without feedback mechanism. (2) Dependence of electric current on horizontal distance calculated with taking into account feedback mechanism.

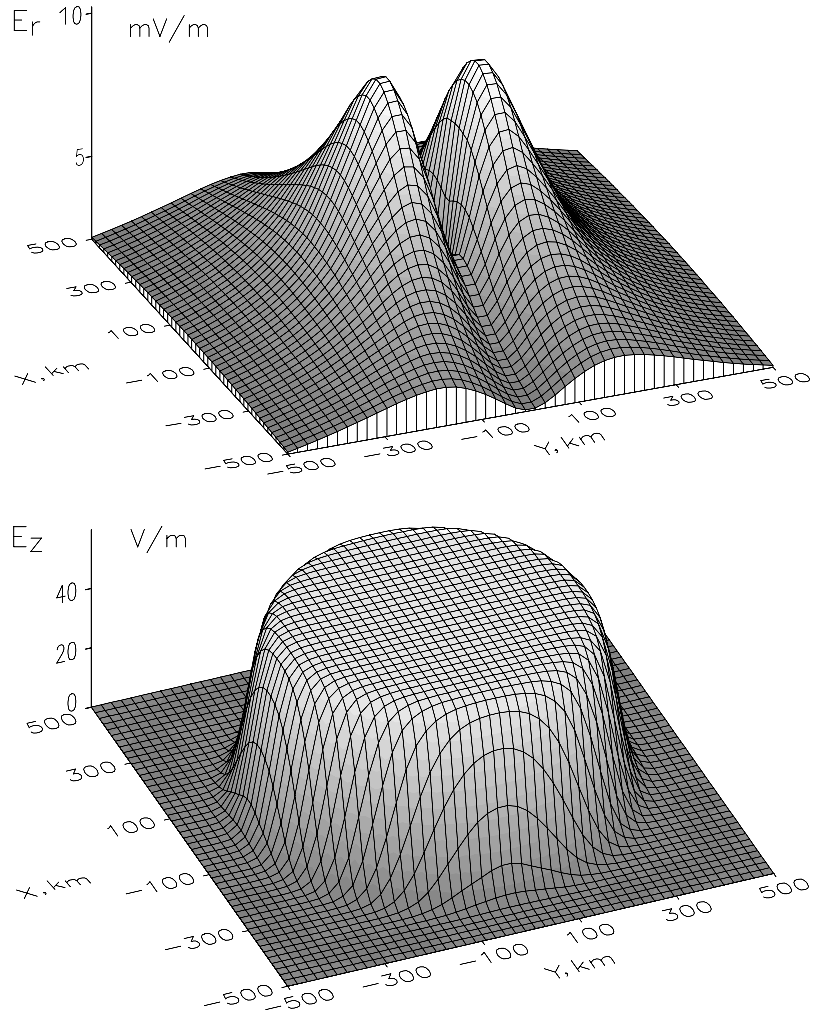

Fig. 5. Spatial distributions of DC electric field calculated for axially symmetric distribution of the external electric current. *Upper panel:* Horizontal component of DC electric field in the ionosphere. Angle of magnetic field inclination is 20°. *Lower panel:* Vertical component of DC electric field on the ground.

This equation allows calculating the vertical electric field component on the Earth surface at the given values of j_{p0}, j_{n0}. Results of calculation of the electric field on the Earth's surface at the given values of j_{p0}, j_{n0} obtained by formulas (8) and (9) are presented in Fig. 4. This figure shows that the feedback between external electric current and the electric field at the Earth surface leads to significant decrease of vertical component of the electric field. According to Sorokin and Yaschenko (2000) and Sorokin et al. (2001) the dependence of external currents formed by positive and negative particles on radial distance r was assumed as

$$j_{\rm p}(r) = j_{\rm p0}\exp(-r^2/r_0^2), \quad j_{\rm n}(r) = j_{\rm n0}\exp(-r^2/r_0^2),$$
$$j_{\rm p0} = 4\pi\sigma_0 eZ_{\rm p}h_{\rm p}N_{\rm p0}, \quad j_{\rm n0}/j_{\rm p0} = 0.64.$$

Let us assume $s_{\rm p,n} = \exp(-z/h_{\rm p,n})$, $\sigma(z) = \sigma_0\exp(z/h)$, then $k_{\rm p,n}/\rho = h_{\rm p,n}/(h + h_{\rm p,n})$. For numerical calculations we select the following parameters:

$$h_{\rm p} = 20\ {\rm km}, \quad h_{\rm n} = 15\ {\rm km}, \quad h = 5\ {\rm km},$$

$$N_{\rm p0} = 8\times 10^3\ {\rm cm}^{-3}, \quad Z = 100,$$

$$\sigma_0 = 2\times 10^{-4}\ {\rm s}^{-1}, \quad \Sigma_{\rm P} = 2\times 10^{12}\ {\rm cm/s}.$$

Calculations show considerable limitation of the electric field magnitude on the Earth's surface when we take into account the feedback mechanism between disturbances of this field and the causal external currents.

The components of DC electric field in the ionosphere:

$$E_x(x,y) = -\partial\varphi_1(x,y)/\partial x,$$
$$E_y(x,y) = -\partial\varphi_1(x,y)/\partial y, \tag{10}$$

and the vertical component of electric field in the atmosphere–ionosphere layer are determined from equations:

$$\left(\frac{1}{\sin^2\alpha}\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\varphi_1(x,y) = -\frac{1}{2\rho\Sigma_{\rm P}}\left[k_{\rm p}j_{\rm p0}(r)\sqrt{1+\frac{E_{z0}(r)}{E_{\rm cp}}} - k_{\rm n}j_{\rm n0}(r)\sqrt{1-\frac{E_{z0}(r)}{E_{\rm cn}}}\right], \tag{11}$$

$$E_z(r,z) = \frac{1}{\sigma(z)}\left[\left(\frac{k_{\rm p}}{\rho} - s_{\rm p}(z)\right)j_{\rm p0}(r)\sqrt{1+\frac{E_{z0}(r)}{E_{\rm cp}}} - \left(\frac{k_{\rm n}}{\rho} - s_{\rm n}(z)\right)j_{\rm n0}(r)\sqrt{1-\frac{E_{z0}(r)}{E_{\rm cn}}}\right]. \tag{12}$$

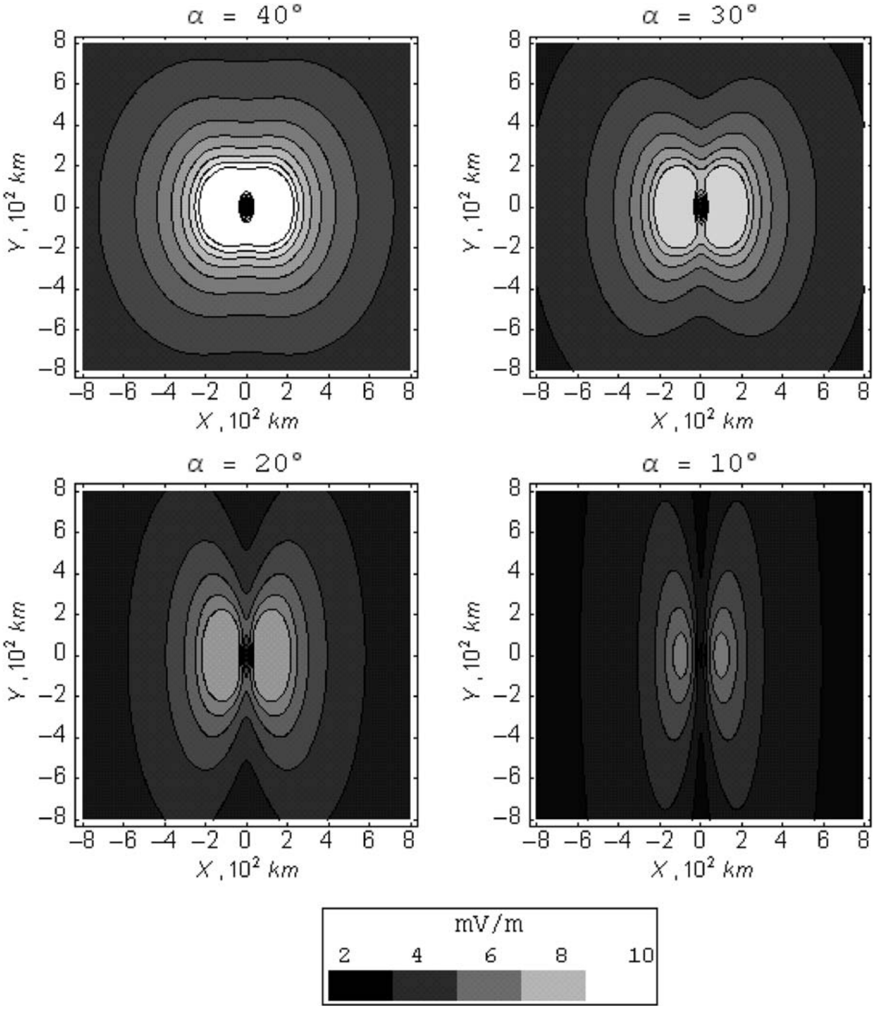

Fig. 6. Spatial distribution of DC electric field in the ionosphere seismic zone calculated for different angles of magnetic field inclination α.

The spatial distribution of DC electric field in the ionosphere and vertical component of electric field on the Earth's surface calculated from (10)–(12) are presented in Fig. 5. These figures show that at the selected parameters the horizontal electric field in the ionosphere reaches ∼10 mV/m, while the vertical electric field on the Earth's surface is limited by magnitude ∼100 V/m. The calculations show that DC electric field in the ionosphere reaches maximal magnitudes at the edges of area of external current. The horizontal scale of vertical electric field enhancement on the ground exceeds about three times the characteristic horizontal scale of external current. Within this area, the vertical field practically does not depend on distance. Distributions of the DC electric field horizontal component in the ionosphere at different angles of magnetic field inclination are presented in Fig. 6. Calculations show that the structure of the horizontal component becomes two-cell (dipole-like). This component in the meridian plane depends on the magnetic field inclination.

4. Conclusions

Convective transport of charged aerosols in the lower atmosphere at different stages of typhoon and earthquake development leads to formation of external electric current. Its inclusion in the atmosphere–ionosphere electric circuit is accompanied by amplification of conductivity current that flows into the ionosphere. The current flowing within the conducted layer of the ionosphere is closed in the conjugate ionosphere through the magnetic field-aligned current.

The computation method presented above allows calculating spatial distribution of the conductivity current and related electric field for arbitrary altitude dependence of atmospheric conductivity and horizontal distribution of external electric current at oblique geomagnetic field. The calculations show that DC electric field in the ionosphere can reach the magnitudes 10–20 mV/m.

Analyses of satellite data have revealed the electric field disturbances up to 20 mV/m in the ionosphere over a typhoon (Isaev et al., 2002a,b; Sorokin et al., 2005b) and earthquake preparation zones (Chmyrev et al., 1989). The papers regarding to hurricane effects on the ionosphere are based on experimental data from COSMOS-1809 satellite. Hundreds of the satellite passages over typhoon and tropical storm zones have been analyzed and practically in each of them, the electric field disturbances have been observed in the ionosphere. Concerning the measurements of vertical electric field at the surface of ocean, we do not know any indications of such works in the literature. It can be expected that the magnitude of such a field reaches up to tens kV/m in the storm area. The calculations given above show that the external electric current arising as a result of charge separation in cumulus within typhoon zone leads to generation of horizontal electric field in the ionosphere. The magnitude and characteristic spatial scale of this field correspond to experimental data obtained from satellite observations. This is why the model considered above can be used for estimation of vertical electric field at the ocean surface below the external current on the basis of satellite measurements of horizontal electric field in the ionosphere. For study of the earthquake effects the ground-based measurements are performed within the area seized by the external current unlike a typhoon in which the external current is located above the Earth surface. In a process of earthquake development the external current arises as a result of emanation of charged aerosols from the lithosphere together with soil gases, their convective transfer and gravitational sedimentation. The ground-based observations did not reveal any significant long-term (1–10 days) electric field disturbances within earthquake area at the distances of tens to hundreds km from epicenter. The field limitation on the Earth surface is caused by feedback mechanism between excited electric field and the causal external current. This feedback is produced by the potential barrier for charged particle at its transfer from ground to the atmosphere. Owing to this mechanism the external current in seismic zone, which is close in magnitude to the current in typhoon area generates strong DC electric field in the ionosphere, while the field generated near the Earth surface is comparable with the background field. The effect of limitation of the vertical electric field magnitude on the ground creates significant advantage for satellite monitoring of seismic related electric field disturbances as compared to ground-based observations. Besides, an amplification of pre-earthquake electric field in the ionosphere can be verified by simultaneous measurements of other electromagnetic and plasma effects sensible to growth of DC electric field. Thus, the ionosphere can be a more efficient indicator of definite class of earthquake precursors than the ground-based observations.

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