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ELECTRIC FIELD DISTURBANCE IN THE EARTH - IONOSPHERE LAYER

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ABSTRACT

Theoretical studies of the electric field disturbance due to a variation of the atmospheric current, flowing between ionosphere and the Earth, are carried out. This variation is caused by a conductivity variation and the electromotive force generation in the near-ground atmospheric layer. The increase of the atmosphere radioactivity level near the ground results in substantial increase of electric field in the lower ionosphere. Electromotive force generation in lower atmosphere leads to field increase or decrease or to the sign change in the ionosphere, depending on its direction and value.

FORMATION OF THE ATMOSPHERIC ELECTRIC FIELD

Pierce (1976) considered the method for monitoring seismic activity based on the registration of the electric conductivity enhancement and the electric field decrease in the near ground atmosphere caused by the radon concentration growth. Molchanov and Hayakawa (1996) discussed the possible mechanisms of amplification of the atmospheric electric field before earthquake. An increase of the lower atmosphere conductivity, as well as the electromotive force generation, results in a redistribution of the atmosphere electric field. This field arises due to presence of a negative charge on the Earth's surface along with the positive charge on the ionosphere lower boundary. Since the Earth's and ionospheric conductivities considerably exceed the atmosphere conductivity, their boundary surfaces form a spherical capacitor with the constant potential difference about 300 kV (Chalmers, 1967). This potential difference is supplied by the upward currents in the zones of increased thunderstorm activity. Since conductivities of the Earth and of the lower ionosphere are high as compared to the atmosphere conductivity, the horizontal currents rapidly (within the periods of the order of 10 s) equalize the horizontal irregularities of the potential on the boundary surfaces of the Earth-ionosphere layer. Hence, these boundaries can be considered as equipotentials. The electric field disturbances outside the thunderstorm activity zones in a plane-layered atmosphere, resulted from slow conductivity variations and dependent on the altitude, are considered below. These variations arise simultaneously within the horizontal scales comparable to the altitude of the lower ionosphere boundary. When induction effects are neglected, electrodynamical processes in the Earth-ionosphere layer are described by the equations:

$$\begin{gathered} \boldsymbol{E} = -\nabla\varphi \; ; \quad \nabla\cdot\boldsymbol{E} = 4\pi(\rho + \rho_s) \; ; \quad \boldsymbol{j} = \sigma\boldsymbol{E} \; ; \\ \partial(\rho + \rho_s)/\partial t + \nabla\cdot(\boldsymbol{j} + \boldsymbol{j}_s) = 0 \; , \\ \partial\rho_s/\partial t + 4\pi\sigma\rho_s + \nabla\cdot\boldsymbol{j}_s = 0. \end{gathered} \tag{1}$$

where $\boldsymbol{E}$, φ are the electric field and its potential, $\boldsymbol{j}$, ρ are the current and charge densities, σ is the atmosphere conductivity, ρ_s, j_s are external charge and current densities arising due to electromotive force (e. m. f). Let us introduce right-hand Cartesian coordinate system with the vertical z-axis directed upward and the zero point located on the ground. The lower ionosphere boundary coincides with the plane $z = h$. In one-dimensional approximation, only the vertical components of the field E and current j differ from zero. Using the continuity condition, we obtain that the current density in the Earth-ionosphere layer is independent of altitude. Since the atmosphere conductivity increases with the altitude, the electric field intensity decreases with the altitude, according to the Ohm's law, as $E(z)=j/\sigma(z)$. The latter equation allows us to derive the relation between the potential difference $U=\varphi(h) - \varphi(0)$ and the field and current values in the Earth-ionosphere layer:

$$U = j\int_0^h \frac{dz}{\sigma(z)}; \quad E(z) = U/\sigma(z)\int_0^h \frac{dz}{\sigma(z)} \tag{2}$$

The altitude distribution of the atmosphere conductivity is denoted as $\sigma(z)$. Undisturbed values of the electric field and the current density are E_0 j_0. From the Eq. 2 and the similar expression for undisturbed quantities we obtain the electric field altitude distribution in the Earth-ionosphere layer:

$$E(z) = \frac{E_0(0)\sigma_0(0)}{\sigma(z)} \frac{\int_0^h \frac{dz}{\sigma_0(z)}}{\int_0^h \frac{dz}{\sigma(z)}} \tag{3}$$

The electric field is varied under action of the e. m. f. arising in the near-ground layer and resulting in the external current. When the e. m. f. sources in the atmosphere are absent, the vertical current j_0 is independent of the altitude z while the vertical component of the electric field $E_0(z)$ is determined by the altitude distribution of conductivity: $E_0(z) = j_0/\sigma(z)$. According to the Ohm's law, the current determines the electric field in the Earth-ionosphere layer: $j_0 = \sigma(z)E_0(z) = \sigma(0)E_0(0)$, where $\sigma(0)$, E_0 are the atmosphere conductivity magnitude and intensity of the vertical electric field near the ground in a case of absence of the e. m. f. sources in the atmosphere. The electric field on the Earth surface is determined according to Eq. 2. In one-dimensional approximation we get from Eq. 1:

$$\begin{aligned} &\left(\frac{\partial}{\partial t} + 4\pi\sigma\right)\frac{\partial E}{\partial z} + 4\pi\frac{d\sigma}{dz}E = -4\pi\frac{\partial j_s}{\partial z}, \\ &\rho = -\rho_s - \frac{1}{4\pi}\frac{\partial E}{\partial z}. \end{aligned} \tag{4}$$

This equation is solved by means of Fourier transform under the condition that the e. m. f. arising in the atmosphere does not change the potential difference between the ionosphere and the Earth surface. Actually, the total resistance of the Earth-ionosphere layer is approximately 200 Ohm, and the resistance of the atmosphere column with the cross-section of the order of hundreds km, enveloping the region of the e. m. f. formation, is considerably higher (about 10 MOhm). In quasi-stationary approximation when the e. m. f. varies slowly with the duration exceeding $1/4\pi\sigma$, this solution has the form:

$$E(z,t) = -E_0(z,t) - \frac{1}{\sigma(z)}\left\{j_s(z,t) - \frac{\int_0^h j_s(z,t)\frac{dz}{\sigma(z)}}{\int_0^h \frac{dz}{\sigma(z)}}\right\} \tag{5}$$

where $E_0(z,t)$ is determined by the potential difference U in Eq. 2. Eq. 5 allows one to derive the time dependent altitude distribution of the electric field if the altitude distribution of external currents is set up.

DISTURBANCE OF THE LOWER ATMOSPHERE CONDUCTIVITY

The lower ionosphere conductivity undergoes the effects of various factors. Among those, there could be variations of radioactivity level and the atmosphere chemical composition, meteorological and dusty conditions etc. These processes accompany the phenomena of catastrophic character such as earthquakes, volcanic eruptions, underground explosions, cyclonic shock fronts and so on. Let us consider, for example, the effects connected with the pre-earthquake processes. Before earthquake the atmosphere radioactivity level is increased in the focal zone with the characteristic scale of the order of hundreds km (Virk and Singh, 1994). Let us introduce the altitude distribution of concentration of the radioactive elements in the atmosphere as the function $n(z)$. During their decay, gamma rays are produced and absorbed due to Compton effect on the air molecules. The distribution function of gamma rays is derived from the transfer equation (Leipunskiy *et. al.*, 1960). The number of quantas in unit volume is determined by integrating the distribution function over the solid angle. As a result of Compton effect in the air, gamma rays generate the flux of energetic electrons. In their motion in the air these electrons loss the energy as a result of collisions; in this case low-energy secondary electrons are produced. Formation of an electron-ion pair in the air consumes 33 eV of the absorbed energy (Massey *et. al.*, 1969). Mean ion production rate at the altitude z under action of ionizing radiation of the atmosphere radioactivity q_a is determined by the equation:

$$q_a(z) = \frac{\lambda\kappa}{2 l_\gamma(z)} \int_0^\infty dz' n(z') \mathbf{E}_1 \left\{ \frac{H}{l_{\gamma g}} \left| e^{-z/H} - e^{-z'/H} \right| \right\} \tag{6}$$

where $\lambda = \varepsilon / 33$ eV, $\kappa = \ln 2 / T$, $l_\gamma(z) = l_{\gamma g} \exp(z/H)$ is the free path length of gamma-rays at the altitude z, ε is the energy of energetic electrons, T is mean decay time of radioactive elements, H is the height of uniform atmosphere, $\mathbf{E}_1(u) = \int_1^\infty \frac{e^{-ux}}{x} dx$. Besides the atmosphere radioactivity, the lower atmosphere is ionized by cosmic rays. The altitude distribution of the ion production rate q_s due to the cosmic ray effect can be approximated by Chapman's function (Ratcliffe, 1960). The total ion production rate in the lower atmosphere $q(z) = q_a + q_s$ is sum of the ion production rates due to resultant effect of the atmosphere radioactivity and cosmic rays. Equilibrium values of concentration of electrons and ions, produced due to these sources, are determined by the processes of their recombination in the air. To estimate the stationary ion-molecular composition of the atmosphere a simplified scheme of ionization-recombination processes (Barth, 1961) was considered. In the atmosphere near the ground besides light single-charged ions, heavy ions produced as a result of adherence of light ions to aerosol. Concentrations of light positive and negative ions n_+, and n_-, forming the lower atmosphere conductivity, are determined, in principle, by their recombination and adherence to aerosol (Tverskoy, 1949). Mean concentration of the soil aerosols exponentially decreases with the altitude (Gavrilova and Ivliev, 1996). The atmosphere conductivity σ is expressed through the light ion concentration according to the equation:

$$\sigma = e(\mu_+ n_+ + \mu_- n_-) \approx e\mu n,$$

where μ is the light ion mobility (Tverskoy, 1949).

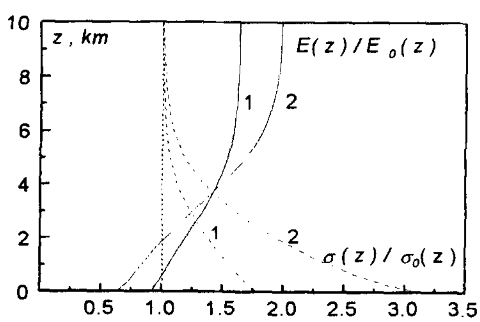

Fig. 1. Altitude profile of the conductivity and the electrical field variations.

Figure 1 represents the results of calculations for the altitude distribution of the conductivity and the electric field variation for typical values of the atmosphere electrophysical parameters. Two cases of increased atmosphere radioactivity level on the Earth's surface are considered: the increase by 2 (curve 1) and 4 (curve 2) times. It is seen from Figure 1 that enhancement of the atmosphere radioactivity near the ground results in a substantial increase of the atmosphere conductivity in the near-ground layer below 5 km and to an increase of electric field in the lower ionosphere.

ELECTROMOTIVE FORCE IN THE NEAR-GROUND LAYER OF THE ATMOSPHERE

One of the mechanisms of the e. m. f. generation in near-ground layer of the atmosphere is caused by soil aerosols injection into the atmosphere. Several days before earthquake concentration of soil aerosols, counting metal ions, in the atmosphere could increase by one-two orders of magnitude (Pulinets *et. al.*, 1994). As a result of turbulent upward transport and gravitational sedimentation, their quasi-stationary altitude distribution $N(z)$ is formed. Turbulent transport is realized at presence of the vertical gradient of the horizontal wind and the atmosphere thermal instability. The equilibrium is settled when the vertical flow of aerosols is balanced by their gravitational sedimentation with the velocity $w = bmg$ (where m is the particle mass, g is the free fall acceleration, $b = =1/4\pi\eta R$ is the aerosol mobility, η is the air viscosity, R is the aerosol particle radius):

$$Nw = -K\frac{\partial N}{\partial z} \tag{7}$$

The data presented by Gavrilova and Ivliev (1996) show that the altitude distribution of concentration of soil aerosols could be presented in the form $N = N_g\, exp(-z/H_a)$. Hence, the effective coefficient of turbulent transfer K is expressed through the scale of the altitude distribution of soil aerosols:

$$K = wH_a = 2H_a g\rho_a R^2/9\eta \tag{8}$$

where ρ_a is the density of an aerosol particle. There are exist both charged and uncharged aerosols. We assume that the effective charge of these aerosols is formed as a result of the balance of their charge-discharge processes. The external current is expressed through concentrations of positively charged N_+ and negatively charged N_- aerosols: $j_s = q_+N_+v - q_-N_-v = =v\rho_s$ (where $q_{+,-}$ is the value of positive and negative particle charge, v is mean vertical velocity of a charged-particle motion). In quasi-stationary approximation we get from Eq. 1:

$$4\pi\sigma\rho_s = -\,\partial j_s/\partial z \tag{9}$$

Since the fluxes $F_{+,-} = vN_{+,-}$ of charged particles are proportional to the gradients of their concentrations: $F_+ = = -K\,\partial N_+/\partial z$; $F_- = -K\,\partial N_-/\partial z$, these equalities give the equation for determining the external current:

$$\frac{\partial}{\partial z}\left[\frac{1}{4\pi\sigma(z)}\frac{\partial j_s(z,t)}{\partial z}\right] - \frac{j_s(z,t)}{K} = 0\,. \tag{10}$$

If the vertical scale of variations of aerosol concentration is less than the scale of conductivity variation, one could set up $\sigma(z) = \sigma_g$ (conductivity on the ground level) in Eq. 10 for estimation. In this case the solution of Eq. 10 has the form:

$$j_s(z,t) = j_s(0,t)\, exp(-\,z/H_j)\,, \tag{11}$$

where $H_j = [K/4\pi\sigma_g]^{1/2} = (R/6)(2H_a g\rho_a/\pi\eta\sigma_g)^{1/2}$. The external charge altitude distribution is determined by the expression:

$$\rho_s(z,t) = \rho_s(0,t)\,[exp(-\,z/H_j) - H_j\,\delta(z)], \tag{12}$$

where $\delta(z)$ is the Dirac delta-function. The values of the external current and charge on the ground are determined by the equation:

$$j_s(0,t) = 4\pi\sigma_g H_j \rho_s(0,t)\,. \tag{13}$$

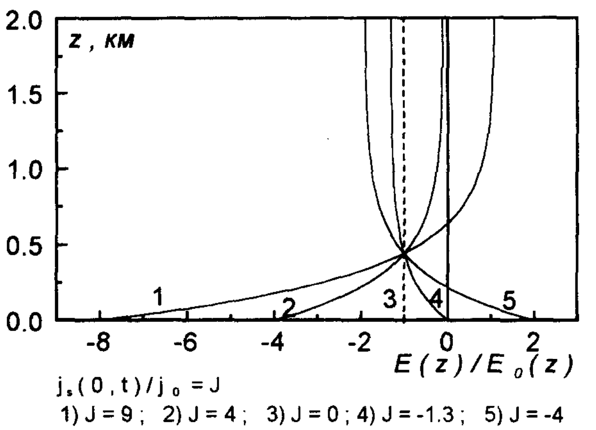

Fig. 2. Altitude dependence of the relative electric field intensity.

External currents and charges are distributed at lower altitudes than the aerosols. This is connected with the fact that charged aerosols are transferred in a conducting medium. Hence, a charge of particles relaxes in the process of their transfer. In Figure 2, the curves of the altitude dependence of the electric field intensity, reduced to its value on the ground, are presented, calculated from Eq.5. The curves correspond to different amplitudes of external current. The graphs show that the field increase on the ground corresponds to its decrease or to the sign change in the ionosphere. If the field on the Earth surface decreases or changes its sign, there will be correspondent growth of its intensity in the ionosphere.

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