**Natural Hazards
and Earth
System Sciences**

A perturbation of DC electric field caused by light ion adhesion to aerosols during the growth in seismic-related atmospheric radioactivity

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Abstract. The influence of variations in conductivity and external electric current variations in the lower atmosphere on DC electric field over a seismic region is investigated. The external current is formed with the occurrence of convective upward transport of charged aerosols and their gravitational sedimentation in the atmosphere. This effect is related with the occurrence of ionization source due to seismic-related emanation of radon and other radioactive elements into the lower atmosphere. An increase in atmosphere radioactivity level results in the appearance of additional sources of ionization, and altitude dependence of the ion formation rate is calculated. Ionization source varies the atmospheric conductivity and the external current through appearance of ions with equilibrium number density and their adhesion to aerosols. We have calculated the perturbation of conductivity and external electric current as a function of altitude. Variation of conductivity and external current in the lower atmosphere leads to a perturbation of electric current which flows in the global atmosphere-ionosphere circuit. Finally, perturbations of DC electric field both on the Earth's surface and in the ionosphere are estimated.

1 Introduction

Starting with Kondo (1968) and Pierce (1976) there have been made some attempts to use DC electric field perturbation over a seismic region for earthquake prediction (Hao, 1988; Pulinets et al., 1994; Molchanov and Hayakawa, 1996; Vershinin et al., 1999; Sorokin and Yaschenko, 2000; Varotsos, 2001). It was discussed (Kondo, 1968; Pierce, 1976) that DC electric field variation could be caused by an increase in the lower atmospheric conductivity as a result of intensive injections of radioactive elements including radon

and aerosols during the preparation stage of earthquakes. According to several previous works, such injections were observed from days to weeks before an earthquake (see, for example, Alekseev and Alekseeva, 1992; Virk and Singh, 1994; Voytov and Dobrovolskiy, 1994; Igarashi et al., 1995; Heincke et al., 1995). Temporal evolution of radon number density in the soil gases and in the spring water were obtained by Virk and Singh (1994), who have shown that radon number density suddenly increased by 2.5 and 1.5 times about one week before an earthquake within 300 km around the epicenter. Heincke et al. (1995) showed that the growth of radon number density by 4 times was observed five days before the earthquake. According to his statistical analyses for 300 micro earthquakes (M<4) the significant growth of radon number density was detected in 75% of the events.

The main ionizing factor determining the level of conductivity in the near surface layer is atmospheric radioactivity. The natural radioactivity of the lower atmosphere is mainly associated with such elements as radon, radium, thorium, actinium and their decay products. Radioactive elements enter the atmosphere together with soil gas, and then they are transferred by air streams upwards up to the altitude of a few km. Therewith the ion production rate amounts to tens of ion pairs in a cubic centimeter per second. An increase in the level of atmospheric radioactivity, e.g. prior to an earthquake, leads to an increase in the ion formation rate. The number density of light ions and the mean charge of aerosols are determined by recombination of ions and their adhesion to aerosols at given ionization sources. Hence, the external electric current formed by charged aerosols and the atmosphere conductivity depend on the ion formation rate. Figure 1 presents a scheme of our model. Electric charge of the moving aerosol is determined by light ions adhesion to this particle. Near-earth atmospheric layer has a small value of conductivity, so that the increase of conductivity of this layer leads to the variation of electric current flowing from the Earth's surface to the ionosphere by this external current

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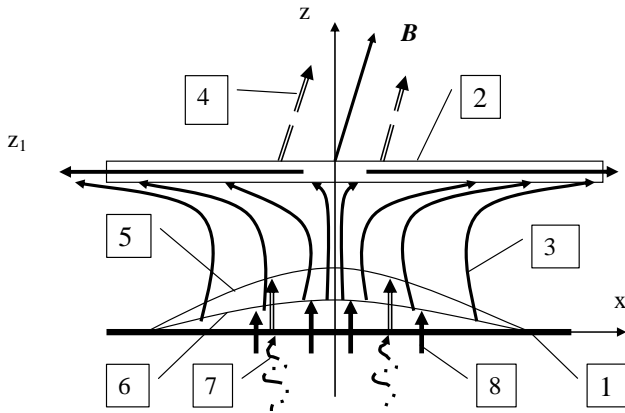
Fig. 1. A schematic illustration of the model used for calculations of radon influences on electric field in the atmosphere - ionosphere circuit. 1 – Earth's surface, 2 – ionosphere, 3 – conducting current in the atmosphere and the ionosphere, 4 – field aligned current ($\mathbf{B}$, Earth's magnetic field) , 5 – zone of upward convection of charged aerosols and external electric current formation, 6 – zone of perturbation of atmospheric conductivity induced by radioactive element emanation, 7 – charged aerosols moving upward with soil gases, 8 – radon emanation.

related to a preparing earthquake (Sorokin et al., 2005a, b). Consequently, this effect yields DC electric field perturbation connected with the conducting current both on the Earth's surface and in the ionosphere.

2 Source of ionization

Below we obtain the vertical distribution of ion production rate as a result of absorption in the atmosphere of the gamma radiation and the alpha particles from the decay of radioactive elements being constituents of the atmospheric radioactivity. We introduce a Cartesian system of coordinates (x, y, z) with the z-axis directing upward as it is shown in Fig. 1. The Earth's surface is taken to be the plane $z=0$. Let us assume that the vertical distribution of radioactive element number density in the atmosphere is determined by the function $N_R(z)$ and the ion production rate under the action of gamma radiation of atmospheric radioactivity is determined by the function $q_\gamma(z)$. Since the initial angular distribution of gamma radiation is isotropic and then the number of quanta N_γ being generated in a unit volume per unit time and per unit solid angle is given by $N_\gamma = \kappa N_R / 4\pi$ ($\kappa = \ln 2/T$, T is an effective half-life period). The gamma radiation is absorbed due to the Compton effect of air molecules by electrons. The distribution function $f(\mathbf{r}, t, \theta)$ of quanta is found from the transfer equation (Leipunsky et al., 1960):

$$\frac{\partial f}{\partial t} + \mathbf{c} \cdot \frac{\partial f}{\partial \mathbf{r}} = -\frac{f}{\tau_\gamma} + N_\gamma; \quad \tau_\gamma = \frac{l_\gamma}{c} \quad , \tag{1}$$

where $\mathbf{c}$ is the velocity of quantum propagation ($|\mathbf{c}| = c$), c is the light velocity, l_γ is the mean free path of a quantum, and θ is an angle between the velocity vector and the z-axis. For an exponentially inhomogeneous atmosphere with the scale height of H the mean free path of a quantum depends on altitude:

$$l_\gamma(z) = l_{\gamma 0} \exp(z/H),$$

where $l_{\gamma 0}$ denotes the mean free path on the Earth's surface. In the one-dimensional and stationary approximation we obtain:

$$\frac{df(z, \theta)}{dz} + \frac{f(z, \theta)}{l_\gamma(z) \cos \theta} = \frac{\kappa}{4\pi\, c \cos \theta} N_R(z). \tag{2}$$

The number of quanta in a unit volume $n_\gamma(z)$ is determined by integrating the distribution function $f(z, \theta)$ over the solid angle:

$$n_\gamma(z) = 2\pi \int_0^\pi f(z, \theta) \sin \theta \, d\theta \quad . \tag{3}$$

As a result of the Compton effect in the air, the gamma radiation generates a flux of fast electrons whose number density $n(z)$ is found from the following formula (Medvedev et al., 1980):

$$n(z) = \frac{l_e(z)}{l_\gamma(z)} n_\gamma(z) = \frac{l_{e 0}}{l_{\gamma 0}} n_\gamma(z),$$

where $l_e(z) = l_{e 0} \exp(z/H)$ is the mean free path of an electron as a function of altitude z of the atmosphere. During the movement in the air, the fast electrons loose energy and, as result of collisions, they produce low-energy secondary electrons. The absorbed energy of fast electrons in the air in a unit volume is $n\varepsilon$; ε is the energy of fast electron. The quantity 33 eV of the absorbed energy is spent in creating an electron-ion pair in the air (Massey et al., 1969). Hence, the number of secondary low-energy electrons in a cubic centimeter produced during the life-time of fast electrons is $n\chi$, where $\chi = \varepsilon/33$ eV. Thus we obtain that the mean rate of secondary electron production q_γ is determined by the equality:

$$q_\gamma(z) = \frac{\chi c}{l_e(z)} n(z) = \frac{\chi c}{l_\gamma(z)} n_\gamma(z)$$

The vertical distribution of concentration of the radioactive elements in the atmosphere is determined by many factors including meteorological conditions, turbulent diffusion, gravity etc. To estimate the effects of increasing atmospheric radioactivity near the Earth's surface on the electric field in the atmosphere, we choose the following altitude dependence of the level of atmospheric radioactivity:

$$N_R = N_{R0} \exp(-z/H_R),$$

where N_{R0} is the radioactive element number density near the Earth's surface. Substituting Eq. (2) into Eq. (3) and integrating over the solid angle (see Appendix A), we obtain

the altitude dependence of the ion production rate under the action of gamma rays of atmospheric radioactivity:

$$q_\gamma = q_{\gamma 0} F \left[\exp\left(-z/H_R \right) \right] / F\,(1);$$
$$F(y) = y \int_0^1 x^{(H/H_R)-1} E_1 \left(\frac{H}{l_{\gamma 0}} |x - y| \right) dx; \qquad , \qquad (4)$$
$$E_1(u) = \int_1^\infty \frac{\exp(-ux)}{x} dx; \quad q_{\gamma 0} = \frac{\chi \kappa H N_{R0} F(1)}{2 l_{\gamma 0}}$$

where $E_1(u)$ is the integral exponential function. The quantity $q_{\gamma 0}$ is the ion production rate on the Earth's surface, and H_R is the spatial scale of altitude dependence of radioactive elements concentration.

Because the mean free path of alpha particles in the air is very small, then the altitude dependence of the ion production rate q_α related to these particles is coincident with the one for the atmospheric radioactivity sources $q_\alpha = q_{\alpha 0} \exp(-z/H_R)$. Apart from the atmospheric radioactivity, the lower atmosphere is ionized by cosmic rays. The vertical distribution of the ion production rate resulted from the action of cosmic rays may be approximated by the Chapman function $Ch(z-z_m)$ (Ratcliffe, 1960) with the altitude of ion production rate with a maximum at z_m and its value at this altitude q_m. The total ion production rate in the lower atmosphere is a sum of ion production rates due to the action of cosmic rays and atmospheric radioactivity:

$$q(z) = q_m Ch(z-z_m) + \frac{q_0}{1+B}(1+A) \left\{ \frac{F\left[\exp\left(-z/H_R\right)\right]}{F(1)} \right.$$
$$\left. + B \exp\left(-\frac{z}{H_R}\right) \right\}. \qquad (5)$$

Indexes A and B in Eq. (5) are determined by formulas:

$$q_{\gamma 0} = q_0 \frac{1+A}{1+B}; \quad q_{\alpha 0} = q_0 B \frac{1+A}{1+B},$$

where q_0 is the background ion production rate in the atmosphere near the Earth's surface, A is the index of growth of radioactivity in the near Earth layer, and B is an index of relative power of ionization sources by gamma radiation and alpha particles. This index is in a range of $0 < B < \infty$; When $B=0$ the ionization is produced only by gamma radiation and the source is alpha particles for $B \to \infty$. Figure 2 presents the example of altitude dependences $q=q(z)$ calculated by Eq. (5) when ion production rates due to the action of alpha particles and gamma rays are equal each other $B=1$. As follows from these plots, the vertical distribution of the ion formation rate is different from the exponential altitude dependence of atmospheric radioactivity. We see a significant increase in ion production rates in maximum.

3 External current and atmospheric conductivity

The formation of external electric current in the atmosphere over a seismic region is connected with turbulent upward
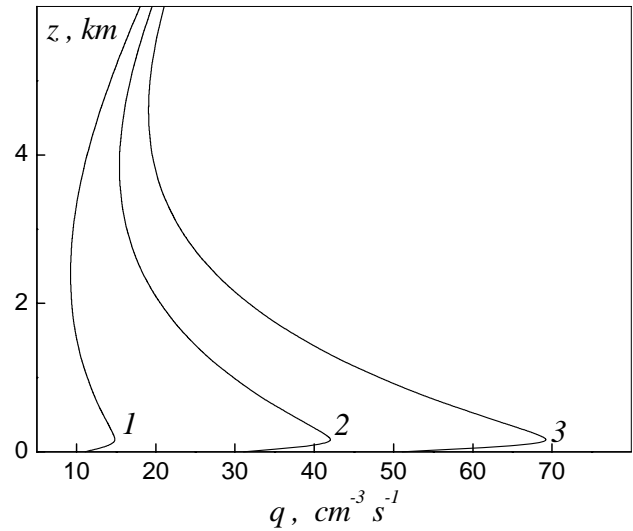
Fig. 2. The altitude dependences of ion production rate at $r=0$. We have chosen, $q_0=10\,\mathrm{cm^{-3}\,s^{-1}}$; $q_m=40\,\mathrm{cm^{-3}\,s^{-1}}$, $B=1$, 1) A=0, 2) A=2, 3) A=4.

transport of charged aerosols injected from the soil accompanying with radon, their gravitational sedimentation and variation of their charge by light ions adhesion. Growth of seismic activity intensifies aerosol injection with the soil gases. This intensification process spreads over an area from tens to hundreds km in diameter. To calculate the external current and the conductivity of atmosphere, it is necessary to find an equilibrium ion number density depending on the ion formation rate. The equilibrium value of ion number density is determined by their recombination processes in the air and adhesion to the aerosols. To estimate the stationary ion composition of the atmosphere, we employ a simplified system of ionization-recombination processes (Barth, 1961). In the atmosphere near the Earth's surface, except light single-charged ions there also exist heavy ions created as a result of adhesion of light ones to aerosols. We consider positive and negative ions with number densities n_+, n_-, respectively, together with aerosols with number density N_j (j number of elementary charges). Ion number densities obey the following equations (Clement and Harrison, 2000):

$$\frac{\partial n_+}{\partial t} + \nabla \cdot J_+ = q - \alpha n_+ n_- - n_+ \sum_{j=-\infty}^{\infty} \int dR \beta_{1,j}(R) N_j(R);$$
$$J_+ = \mu_+ n_+ E;$$
$$\frac{\partial n_-}{\partial t} + \nabla \cdot J_- = q - \alpha n_+ n_- - n_- \sum_{j=-\infty}^{\infty} \int dR \beta_{-1,j}(R) N_j(R);$$
$$J_- = -\mu_- n_- E \qquad (6)$$

where $N_j(R)$ is the number density distribution of aerosols versus charges j and their radius R, E is the electric field, J_+, J_- are the electric current densities of the positive and negative ions respectively. The second term on the right-hand

side represents removal rate by recombination with a rate constant α, and the final terms represent attachment to a joint aerosol charge with ion attachment coefficients β_{1j}, β_{-1j} as given by Gunn (1954):

$$\beta_{1j} = \frac{je\mu_+}{\varepsilon_0\left[\exp(2\lambda j) - 1\right]}; \quad \beta_{-1j} = \frac{je\mu_-}{\varepsilon_0\left[1 - \exp(-2\lambda j)\right]};$$

$$\lambda = \frac{e^2}{8\pi\varepsilon_0 RkT}. \tag{7}$$

In Eq. (7) e is the electron charge, ε_0 is the permittivity of the vacuum, μ_+, μ_- are positive and negative ion mobility respectively, T is the temperature, and k is the Boltzmann constant. The equation presenting motion of aerosols with j units of charge and radius R has the following form (Clement and Harrison, 2000):

$$\frac{\partial N_j}{\partial t} + \nabla \cdot \boldsymbol{J}_j = \beta_{1j-1}n_+N_{j-1} - \beta_{-1j}n_-N_j - \beta_{1j}n_+N_j$$
$$\qquad + \beta_{-1j+1}n_-N_{j+1} \tag{8}$$
$$\boldsymbol{J}_j = N_j\boldsymbol{v}(R) - K(R)\nabla \cdot N_j$$

Let us assume that the mean velocity of aerosol motion in the atmosphere is a sum $\boldsymbol{v} = \boldsymbol{w} + \boldsymbol{v}_c$, where $\boldsymbol{w} = (m/4\pi R\eta)\,\boldsymbol{g}$ is the velocity of aerosol sedimentation, $m = (4/3)\pi R^3 \rho_a$ is the mass of aerosol, ρ_a is the aerosol density, η is the viscosity coefficient, $\boldsymbol{g}$ is the gravitational acceleration, $\boldsymbol{v}_c$ is the mean velocity of upward aerosols motion as a result of atmosphere convection, and K is the coefficient of molecular and turbulent diffusion.

We consider the atmosphere volume in which aerosols are missing. Equations (6) allow us to obtain:

$$\frac{\partial(n_+ - n_-)}{\partial t} + \nabla \cdot (\mu_+ n_+ + \mu_- n_-)\,\boldsymbol{E} = 0.$$

Poisson's equation for the field must be added to the ion equations:

$$\nabla \cdot \boldsymbol{E} = (e/\varepsilon_0)(n_+ - n_-).$$

From these equations one finds:

$$\frac{\partial \boldsymbol{E}}{\partial t} = -\frac{\sigma}{\varepsilon_0}\boldsymbol{E}; \quad \sigma = e(\mu_+ n_+ + \mu_- n_-),$$

where σ is the atmosphere conductivity. According to this equation the electric field relaxation is established for the time of ε_0/σ. Then electric field is vanished and the number density of positive and negative charged aerosols is equal ($n_+ = n_- = n$). We denote R_p and R_n as the radius of positive and negative aerosols, respectively. The distribution of aerosols versus charges and radii can be presented by the following formulas:

$$N_j(R) = N_j\left[\Theta(j)\delta(R - R_p) + \Theta(-j)\delta(R - R_n)\right];$$
$$\Theta(j > 0) = 1; \quad \Theta(j < 0) = 0 \tag{9}$$

where $\Theta(x)$ is the unit function, and $\delta(x)$ is the delta function. Substituting Eqs. (9), (6) and assuming $\mu_+ = \mu_- = \mu$ in

a stationary approximation one finds:

$$q - \alpha n^2 - n\mu\frac{e}{4\varepsilon_0}\sum_{j=0}^{\infty}\left[jN_j\frac{\sinh(2j\lambda_p)}{\sinh^2(j\lambda_p)} + jN_{-j}\frac{\sinh(2j\lambda_n)}{\sinh^2(j\lambda_n)}\right] = 0;$$

$$\lambda_{p,n} = \frac{e^2}{8\pi\varepsilon_0 R_{p,n}kT}. \tag{10}$$

We assume that both positive and negative aerosols are injected in the atmosphere. We denote their total number density as $N_p = \sum_{j=0}^{\infty}N_j$ and $N_n = \sum_{j=0}^{\infty}N_{-j}$. The mean charge of aerosols $Z_{p,n}$ is obtained by the formulas:

$$Z_p = \sum_{j=0}^{\infty}jN_j\bigg/N_p; \quad Z_n = \sum_{j=0}^{\infty}jN_{-j}\bigg/N_n.$$

The equations for $N_{p,n}$ are obtained by summing Eq. (8) over j separately for positive and negative charges when the charging terms vanish to leave and then integrating over R:

$$\frac{\partial N_{p,n}}{\partial t} + \nabla \cdot (\boldsymbol{v}_{p,n}N_{p,n}) - \nabla \cdot (K_{p,n}\nabla \cdot N_{p,n}) = 0;$$

$$\boldsymbol{v}_{p,n} = \boldsymbol{v}(R_{p,n}), \quad K_{p,n} = K(R_{p,n}) \tag{11}$$

To obtain the equations for temporal evolution of the positive charge density $\rho_p = eZ_p N_p$ and the negative charge density $\rho_n = eZ_n N_n$ we multiply Eq. (8) by j and sum. Integrating over R one finds:

$$\frac{\partial \rho_p}{\partial t} + \nabla \cdot \boldsymbol{j}_p = \frac{e^2}{\varepsilon_0}\left[\mu_+ n_+ \sum_{j=0}^{\infty}\frac{jN_j}{\exp(2\lambda_p j) - 1}\right.$$
$$\left. - \mu_- n_- \sum_{j=0}^{\infty}\frac{jN_j}{1 - \exp(-2\lambda_p j)}\right]$$
$$\frac{\partial \rho_n}{\partial t} + \nabla \cdot \boldsymbol{j}_n = \frac{e^2}{\varepsilon_0}\left[\mu_- n_- \sum_{j=0}^{\infty}\frac{jN_{-j}}{\exp(2\lambda_n j) - 1}\right. \tag{12}$$
$$\left. - \mu_+ n_+ \sum_{j=0}^{\infty}\frac{jN_{-j}}{1 - \exp(-2\lambda_n j)}\right]$$
$$\boldsymbol{j}_p = \rho_p\boldsymbol{v}_p - K_p\nabla\rho_p; \quad \boldsymbol{j}_n = \rho_n\boldsymbol{v}_n - K_n\nabla\rho_n$$

where $\boldsymbol{j}_p$ and $\boldsymbol{j}_n$ are the densities of external currents which are formed by positive and negative charged aerosols, respectively.

We assume that all quantities in Eqs. (12) are changed more rapidly in vertical direction than in horizontal one. Substituting Eqs. (11) and (12) for symmetrical ions $\mu_+ n_+ = \mu_- n_- = \mu n$ (Clement and Harrison, 1992) in a stationary approximation one obtains:

$$N_{p,n}(z) = N_{p,n}(0)\exp\left(-\int_0^{\infty}\frac{dz}{H_{p,n}}\right);$$
$$H_{p,n} = K_{p,n}/v_{p,n}$$
$$\frac{dj_{p,n}}{dz} = -\frac{e}{\varepsilon_0}\mu n\rho_{p,n}; \tag{13}$$
$$j_{p,n} = -v_{p,n}\rho_{p,n} - K_{p,n}\frac{d\rho_{p,n}}{dz}$$

where $N_{p,n}(0)$ are the positive and negative aerosols number density on the Earth's surface. The ion number density is determined by Eq. (10) which is simplified for the

charge limitation $\lambda_{p,n}j \ll 1$. According to the estimate, for $R=2.5\times 10^{-5}m$ parameter $\lambda=8.351/R(\mu m)T(K)\approx 10^{-3}$. Hence, we obtain for $j<500$

$$n^2 + n\frac{e\mu}{2\alpha\varepsilon_0}\left(\frac{N_p}{\lambda_p}+\frac{N_n}{\lambda_n}\right)-\frac{q}{\alpha}=0. \tag{14}$$

Substituting Eqs. (13) and (14) one obtains the equations for external currents of positive and negative charged aerosols:

$$H_{p,n}\frac{d}{dz}\left(\frac{1}{\sigma}\frac{dj_{p,n}}{dz}\right)+\frac{1}{\sigma}\frac{dj_{p,n}}{dz}-\frac{j_{p,n}}{2\varepsilon_0 v_{p,n}}=0; \;\; \sigma=2e\mu n,$$
$$n=\sqrt{N^2+n_0^2}-N; \;\; N=\frac{e\mu}{4\varepsilon_0\alpha}\left(\frac{N_p}{\lambda_p}+\frac{N_n}{\lambda_n}\right); \;\; n_0=\sqrt{\frac{q}{\alpha}}, \tag{15}$$

where $\sigma=2e\mu n$ is the atmospheric conductivity, and n_0 is the ion number density in the clean atmosphere without aerosols. Equations (15) allow us to calculate the altitude distributions of external current formed by aerosols at a given source of ionization in the atmosphere. This current depends on atmospheric conductivity disturbed by the source of ionization.

4 DC electric field

According to Eqs. (15) the atmospheric conductivity $\sigma(z)$ is expressed in terms of the light ion concentration by the formula:

$$\sigma = 2e\mu\left(\sqrt{N^2+n_0^2}-N^2\right) \tag{16}$$

where $\mu=\mu_0\exp(z/H)$ and $\mu_0=10^{-4}\,\mathrm{m^2\,s^{-1}\,V^{-1}}$ is the light ion mobility in the atmosphere (Meyerott et al., 1980). The vertical distribution of the average number density of soil aerosols is presented by Gavrilova and Ivlev (1996), who have indicated an exponential dependence of the aerosols number density on altitude $N(z)=N_0\exp(-z/H_a)$, where H_a is the spatial scale of altitude distribution. The altitude dependence of the effective recombination coefficient α is represented by the equation $\alpha(z)=\left[5\times 10^{-8}+2.5\times 10^{-6}\exp(-z/H)\right]\,\mathrm{cm^3\,s^{-1}}$ (Smith and Adams, 1982), where $H=7.5\,\mathrm{km}$ is the spatial scale of the exponentially inhomogeneous atmosphere. Figure 3 (upper panel) illustrates the calculation results of conductivity derived by Eq. (16). The ionizing source is described by Eq. (15). The following parameters were chosen: the aerosol number density over the Earth's surface $N_0=2\times 10^3\,\mathrm{cm^{-3}}$, the spatial scale of their vertical distribution $H_a=5\,\mathrm{km}$; the coefficient of light ion adhesion to aerosols $\beta=4.3\times 10^{-6}\,\mathrm{cm^3\,s^{-1}}$, $q_m=40\,\mathrm{cm^{-3}\,s^{-1}}$, $z_m=14\,\mathrm{km}$, $H_R=2\,\mathrm{km}$, $q_0=10\,\mathrm{cm^{-3}\,s^{-1}}$, $B=1$. It follows from the plots that a rapid growth of the conductivity is observed in the surface layer. In the altitude range up to 6 km we observe an increase in the conductivity with the growth of the radioactivity level. Figure 3 (down panel) illustrates the calculation results of conductivity derived by Eq. (16) for the different number density of charged aerosols. Growth of the aerosols number density in the atmosphere leads to decrease
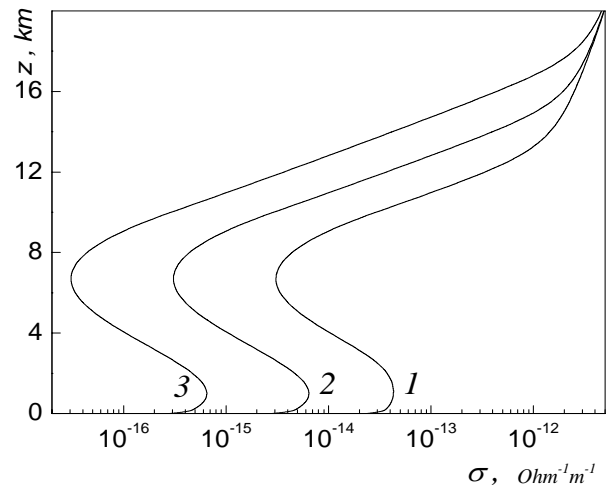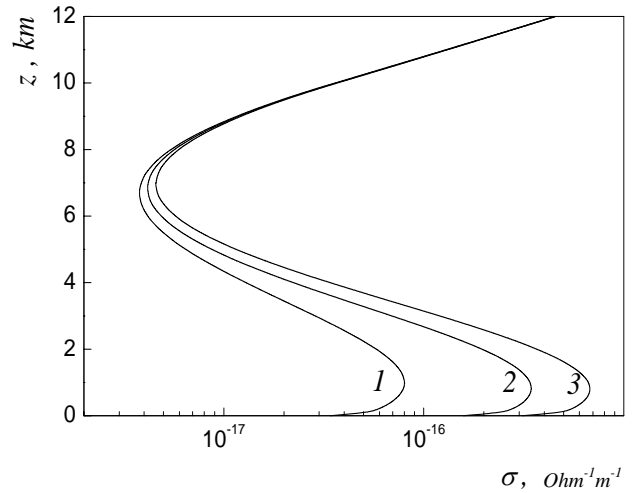

Fig. 3. The altitude dependences of atmosphere conductivity at $r=0$. On the upper panel it is presented atmosphere conductivity at the different level of atmospheric radioactivity. We have chosen, $N_0=2\times 10^3\,\mathrm{cm^{-3}}$; 1) A=0, 2) A=2, 3) A=4. On the down panel it is presented atmosphere conductivity at the different number density of charged aerosols over Earth's surface. We have chosen, A=0; 1) $N_{p0}=10\,\mathrm{cm^{-3}}$, 2) $N_{p0}=100\,\mathrm{cm^{-3}}$, 3) $N_{p0}=1000\,\mathrm{cm^{-3}}$; $N_{n0}=0.64\,N_{p0}$.

of conductivity by loss of the light ions caused by their adhesion to aerosols.

Let us consider for simplicity a large-scale external electric current with axial-symmetric distribution in the horizontal plane with the geomagnetic field directed vertically.

$$j_e(r,z) = j_p(r,z) - j_n(r,z),$$

where $j_p(r,z)$ and $j_n(r,z)$ are the currents of positive and negative charged aerosols, which are determined by Eqs. (15), j_e is the total external current, and r is the
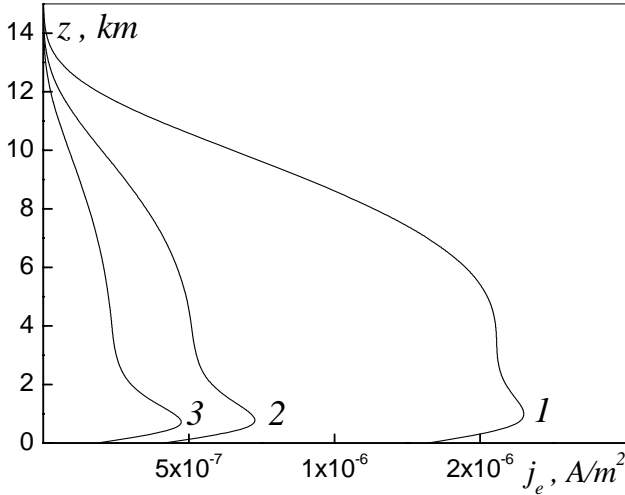
Fig. 4. The altitude dependences of external electric current at $r=0$. We have chosen, 1) A=0, 2) A=2, 3) A=4.

coordinate in horizontal direction. Sorokin et al. (2005a) and Sorokin et al. (2005b) have shown that external current depends on the vertical component of electric field on the Earth's surface. Such a 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 and leads to limitation of vertical electric field on the Earth surface. Their upward movement is performed due to viscosity of soil gases flowing into the atmosphere. If, for example, positively charged particle moves from the ground to the atmosphere, the Earth surface is charged negatively. The resulting downward electric field prevents particles from penetration through the surface. At the same time this field stimulates the going out on the surface of negatively charged particles. In the presence of such a coupling the dependence of external currents magnitude on vertical component of the electric field on the surface can be presented qualitatively by the following formulas (Sorokin et al., 2005a):

$$
\begin{aligned}
&j_p(r,z) = j_{p0}(r)\sqrt{1+\frac{E_0}{E_c}}\, s_p(z); \\
&j_n(r,z) = j_{n0}(r)\sqrt{1-\frac{E_0}{E_c}}\, s_n(z) \\
&s_p(z=0) = s_n(z=0) = 1; \quad E_z(r, z=0) = E_0(r)
\end{aligned} \quad (17)
$$

where j_{p0} and j_{n0} are determined by the injection intensity of aerosols in the absence of the electric field influence. Critical field E_c can be estimated from the balance between viscosity, gravity and electrostatic forces. Viscosity force connected with elevated soil gases acts in upward direction, while gravity force is directed downward, and electrostatic force connected with going out of positive particles is directed downward. Electric field on the Earth's surface can be found from the current continuity equation in the atmosphere – ionosphere layer:

$$
\begin{aligned}
&\frac{d}{dz}(\sigma E_z + j_e) = 0; \quad \sigma E_z + j_e = \sigma_0 E_0 + j_{e0}, \\
&\sigma_0 = \sigma(z=0); \quad j_{e0} = j_e(z=0)
\end{aligned} \quad (18)
$$

Since electric potential of the ionosphere $U = -\int_0^{z_1} E_z dz$ is not changed at the occurrence of external current, substitution of Eq. (17) into Eq. (18) and integration of Eqs. (18) allow us to obtain:

$$
\begin{aligned}
E_0(r) = &-\frac{U}{\rho\sigma_0} - \left(j_{p0}(r)\frac{\rho-k_p}{\rho\sigma_0}\sqrt{1+\frac{E_0(r)}{E_c}}\right. \\
&\left. -j_{n0}(r)\frac{\rho-k_n}{\rho\sigma_0}\sqrt{1-\frac{E_0(r)}{E_c}}\right), \\
\rho = &\int_0^{z_1}\frac{dz}{\sigma(z)}; \quad k_{p,n} = \int_0^{z_1}\frac{s_{p,n}(z)dz}{\sigma(z)};
\end{aligned} \quad (19)
$$

Equation (19) allows one to calculate horizontal distribution of the vertical electric field on the Earth's surface for given j_{p0}, j_{n0} taking into account the feedback effect. Let us assume that the height dependence of external currents and atmospheric conductivity have a form:

$$
s_{p,n} = \exp(-z/h_{p,n}); \quad \sigma(z) = \sigma_0 \exp(z/h),
$$

where $h_{p,n}$, h are the vertical scales of spatial distribution of external currents and the conductivity in the atmosphere. From these equalities we obtain:

$$
\rho = \frac{h}{\sigma_0}; \quad k_p = \frac{hh_p}{\sigma_0(h_p+h)}; \quad k_n = \frac{hh_n}{\sigma_0(h_n+h)}.
$$

According to Sorokin et al. (2005a, b) the horizontal component of DC electric field in the ionosphere is connected with vertical component of field on the Earth's surface by the following formula:

$$
\begin{aligned}
E_r(r) = \frac{1}{2\rho\Sigma_P r}\int_0^r dr'r'&\left[j_{p0}(r')k_p\sqrt{1+\frac{E_0(r')}{E_c}}\right. \\
&\left. -j_{n0}(r')k_n\sqrt{1-\frac{E_0(r')}{E_c}}\right];
\end{aligned} \quad (20)
$$

The external currents are determined from Eqs. (15). We choose $K_p=K_n=K$ for the calculations, and following Junge (1963), $K(z)=K_0\exp(z/H)$ and $K_0=10^5$ cm^2 s^{-1}. The velocity of aerosol sedimentation is estimated by the formula:
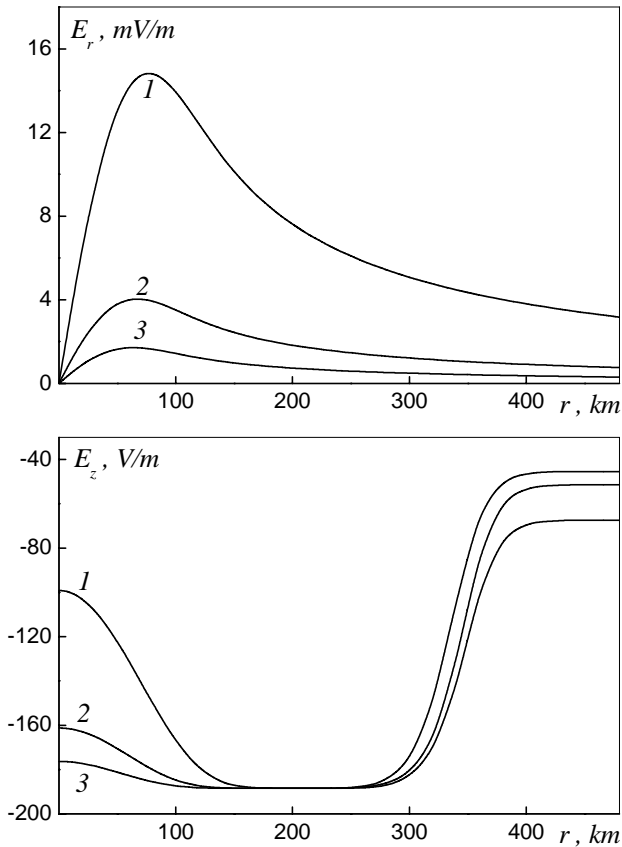
$$
w_{p,n} = \frac{g\rho_a}{3\eta}R_{p,n}^2 = \left[1.2\times10^6\,R_{p,n}^2(\text{cm}^2)\exp(z/H)\right]\text{cm/s},
$$

Altitude dependence of the velocity of atmospheric convection is chosen by,

$$
\begin{aligned}
&v_c(z) = \begin{cases} v_0\sin(\pi z/H_c), & z < H_c \\ 0, & z > H_c \end{cases}, \\
&v_0 = 4\text{ cm/s}; \quad H_c = 10\text{ km}
\end{aligned}
$$

Equation (15) has to be solved with the boundary conditions:

$$
\begin{aligned}
&j_p(z=0) = j_{p0}\sqrt{1+\frac{E_0}{E_c}}; \quad j_n(z=0) = j_{n0}\sqrt{1-\frac{E_0}{E_c}}; \\
&j_{p,n}(z\to\infty) = 0,
\end{aligned}
$$

Fig. 5. The radial dependences of electric field radial component in the ionosphere (upper panel) and vertical component on the Earth's surface (down panel). We have chosen, 1) A=0, 2) A=2, 3) A=4.

where electric field on the Earth's surface E_0 is determined by Eqs. (19) and ionizing source is determined by Eq. (5). We choose a radial dependence of external current as given by,

$$j_{p0}(r)=j_{p0}(0)\exp(-r^2/r_0^2); \quad j_{no}(r)=j_{n0}(0)\exp(-r^2/r_0^2).$$

Numerical solution of this problem was performed by an invariant embedding method (Angel and Bellman, 1972). The following parameters were chosen according to Sorokin et al. (2005a): $B=1$, $R_p=10^{-3}$ cm, $R_n=1.2\times10^{-3}$ cm, $j_{n0}(0)/j_{p0}(0)=0.64$, $U=3\times10^5$ V, $E_c=450$ V/m, $h_p=15$ km, $h_n=10$ km, $h=5$ km, $N_{p0}=8\times10^3$ cm^{-3}, $Z_p=100$, $\sigma_0=2\times10^{-4}$ s^{-1}. Figure 4 illustrates the computational results of external electric current at $r=0$. One can see a significant quantity in current up to the altitudes of 12–14 km, and we notice a maximum of current quantity at the altitude 1–2 km. External current is decreased depending on the growth of the level of atmospheric radioactivity. This result can be explained by the fact that external current depends on the conductivity according to Eq. (15). Figure 5 shows the dependence of $E_r(r)$ (upper panel) and $E_z(r)$ (down panel) for the growth in radon level by two and four
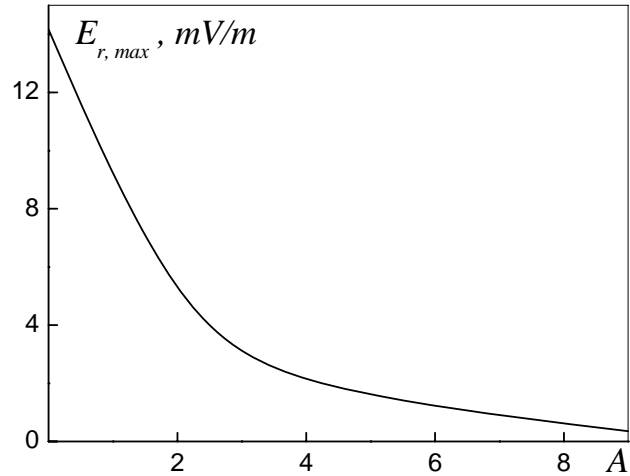
Fig. 6. Dependence on the level of atmospheric radioactivity (A) of electric field horizontal component in the ionosphere.

times. Calculations were performed by using Eqs. (19) and (20), in which the following parameters were chosen: $\Sigma_P=10^{12}$ cm/s, $r_0=100$ km. Figure 5 (down panel) shows that the amplitude of electric field on the Earth's surface is decreased with the radioactivity level inside the disturbed region in spite of the growth in atmospheric conductivity. It can be explained by the variation of the external current. The field does not depend on this level at the boundary of the region. DC electric field in the ionosphere is reduced depending on the radioactivity level in comparison with the behavior of field on the Earth's surface. This dependence is calculated and illustrated in Fig. 6, where the parameter A in Eq. (15) indicates the rate of radioactivity level growth in the near ground atmosphere.

5 Conclusion

According to Sorokin et al. (2005a, b) the convective transport of charged aerosols forms the external electric current in the lower atmosphere. Aerosols are injected into the atmosphere by soil gases in a seismic region. The external current is a source of conductivity current which flows in the atmosphere-ionosphere electric circuit. The horizontal component of DC electric field of this current in the ionosphere reaches up to tenths mV/m, while its vertical component is limited in a volume of the order of 100 V/m. Radon can be injected to the atmosphere accompanying with the soil charged aerosols. In this paper it has been shown that the radon emanation in the lower atmosphere leads to the perturbation of DC electric field both on the Earth's surface and in the ionosphere over a seismic region. Radon emanation is accompanied by an injection to the atmosphere of other radioactive elements which form atmospheric radioactivity in the near ground level. Ionizing sours of radioactivity produce light

ions in the atmosphere. Appearance of the light ions and their adhesion to the aerosols result in the variation of DC electric field by changing the external current and conductivity in the lower atmosphere. In this paper we consider slowly varying (from one to ten days) and large scale (from ten to hundred km) variations of radon emanation in the seismic region and its influence on DC electric field in the atmosphere and the ionosphere. Such scales of radioactive elements emanation including radon is established by their mixing by winds in the atmosphere over a seismic region. As a result we have an increase in radioactivity level. It has been shown that the increasing of radioactivity level leads to the growth in conductivity and module of electric field inside the seismic region in the lower atmosphere, while electric field is reduced in the ionosphere. We obtain a significant variation of DC electric field in comparison with the case of radon emanation missing in the seismic region. According to our calculations the DC electric field can reaches $10\,\mathrm{mV/m}$ in the ionosphere if the field magnitude does not exceed $100\,\mathrm{V/m}$ on the Earth's surface. Our theory of DC electric field amplification and penetration in the ionosphere is based on follows.

1. Electric field in the ionosphere and on the Earth's surface is a field of conductivity current flowing in the atmosphere-ionosphere circuit.

2. The source of conductivity current is an external current including in this circuit.

3. The external current is formed by convective transport of the charged aerosols and the radioactive elements which are injected along with soil gases from lithosphere into the lower atmosphere.

4. 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.

So, we have proposed in this paper a new mechanism of perturbation of electric field by growth of ionizing sources in the atmosphere.

Appendix A

To solve Eq. (2) let us introduce Green function using the formula:

$$f(z, \theta) = \frac{\kappa}{4\pi c \cos\theta} \int\limits_0^\infty dz' N_R(z') G(z, z', \theta), \qquad (A1)$$

where Green function $G(z, z', \theta)$ is determined from the equation:

$$\frac{dG(z, z', \theta)}{dz} + \frac{G(z, z', \theta)}{l_\gamma(z)\cos\theta} = \delta(z - z'). \qquad (A2)$$

In Eq. (A2) $\delta(z-z')$ is Dirak function. Integrating Eq. (A2) on a thin layer near $z=z'$ enables to transform one in the system of uniform equation and the boundary condition:

$$\frac{dG}{dz} + \frac{1}{l_\gamma(z)\cos\theta}G = 0;$$

$$G(z = z' + 0, z', \theta) - G(z = z' - 0, z', \theta) = 1. \qquad (A3)$$

Let us present a solution of the system (A3) in the form of two functions in the angular intervals $0 < \theta < \pi/2; \quad \pi/2 < \theta < \pi$, respectively:

$$G(z, z', \theta) = \begin{cases} G^+, & 0 < \theta < \pi/2 \\ G^-, & \pi/2 < \theta < \pi \end{cases}$$

Such form of the solution means that the function G^+ differs from zero at $z > z'$ and G^- is not equal to zero at $z < z'$. From Eqs. (A3) we obtain:

$$G^\pm(z, z', \theta) = \pm \exp\left\{ -\int\limits_{z'}^z \frac{du}{l_\gamma(u)\cos\theta} \right\}$$

Substituting $l_\gamma(z) = l_{\gamma\,0}\exp(z/H)$ to this equality we obtain an evident dependence of the Green function on z:

$$G^\pm(z, z', \theta) = \pm \exp\left\{ \frac{H}{l_{\gamma 0}\cos\theta}\left[\exp\left(-\frac{z}{H}\right) - \exp\left(-\frac{z'}{H}\right)\right] \right\}$$

Hence, the distribution function $f(z, \theta)$ could be presented in the form of two functions in the different intervals of the solid angle:

$$f(z, \theta) = \begin{cases} f^+, & 0 < \theta < \pi/2 \\ f^-, & \pi/2 < \theta < \pi \end{cases},$$

where it is denoted:

$$f^+(z, \theta) = \frac{\kappa}{4\pi c \cos\theta} \int\limits_0^z dz' N_R(z') \exp\left\{ \frac{H}{l_{\gamma 0}\cos\theta} \right.$$

$$\left. \left[\exp\left(-\frac{z}{H}\right) - \exp\left(-\frac{z'}{H}\right)\right] \right\}$$

$$f^-(z, \theta) = -\frac{\kappa}{4\pi c \cos\theta} \int\limits_z^\infty dz' N_R(z') \exp\left\{ \frac{H}{l_{\gamma 0}\cos\theta} \right.$$

$$\left. \left[\exp\left(-\frac{z}{H}\right) - \exp\left(-\frac{z'}{H}\right)\right] \right\} \qquad (A4)$$

The number of gamma quanta in a unit volume $n_\gamma(z)$ is determined by Eq. (3):

$$n_\gamma(z) = 2\pi \int\limits_0^{\pi/2} f^+(z, \theta)\sin\theta\, d\theta + 2\pi \int\limits_{\pi/2}^\pi f^-(z, \theta)\sin\theta\, d\theta. \quad (A5)$$

Substituting Eqs. (A4) in the integrals (A5) and changing the order of integrating on the variables z and θ, we obtain:

$$n_\gamma(z) = \frac{\kappa}{2c} \int\limits_0^\infty dz' N_R(z') \boldsymbol{E}_1 \left\{ \frac{H}{l_{\gamma 0}} \left[\exp\left(-\frac{z}{H}\right) \right.\right.$$
$$\left.\left. - \exp\left(-\frac{z'}{H}\right) \right] \right\}, \tag{A6}$$

where $\boldsymbol{E}_1(u) = \int\limits_1^\infty \frac{\exp(-ux)}{x} dx$ is the integral power function.
We choose the following altitude dependence of the level of atmospheric radioactivity $N_R = N_{R0} \exp(-z/H_R)$. The mean rate of secondary electron production q_γ is determined by the equality:

$$q_\gamma(z) = \chi c n_\gamma(z) / l_\gamma(z). \tag{A7}$$

Substituting Eq. (A6) into Eq. (A7) we obtain Eq. (4). We were determined a new variable by formula $x = \exp\left(-z/H\right)$ at derivation of Eq. (4).

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