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Modeling electrostatic-photochemistry seismoionospheric coupling in the presence of external currents

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Abstract

In this paper we propose a new 3D model for the generation of electrostatic field in the lithosphere–atmosphere–ionosphere (LAI) system by two external electric sources; namely lithospheric electric field or external current placed near the ground and (simultaneously) in the mesosphere/lower ionosphere. Then we present the results of numerical calculations. We discuss an influence of the generated electric field on the photochemical and ionospheric characteristics in the altitude range of the lower ionosphere. Appearance of strong electric field and strong change of the ionospheric characteristics (such as electron temperature and concentration) in the lower ionosphere is predicted in the presence of external electric sources in the lower atmosphere and mesosphere. An influence of the excited electric field on the losses of VLF electromagnetic waves propagating in the "Earth–ionosphere" waveguide is considered qualitatively, and rough estimation of this phenomenon is carried out. We prove a possibility of "blooming" of the ionosphere for VLF waves, if in the presence of mesospheric external current, an additional external (seismogenic) electric source appears in the lower atmosphere.

Keywords: Lithosphere–atmosphere–ionosphere system; Electrostatic-photochemistry model; Seismoionospheric coupling; External electric sources; VLF

1. Introduction

During the last years, first direct evidences of seismoionospheric coupling appeared (Molchanov et al., 2001; Mikhailov et al., 2003, 2004; Hayakawa, 2004). A few mechanisms, in particular electromagnetic (Molchanov et al., 1995; Grimalsky et al., 1999a,b), acoustic-gravity waves (Molchanov, 2004; Rapoport et al., 2004a) and electrostatic-photochemical (Martynenko et al., 1996; Grimalsky et al., 2003; Rapoport et al., 2004b) channels have been discussed in connection with the phenomena observed in the system "lithosphere–atmosphere–ionosphere–magnetosphere" (LAIM) (Grimalsky et al., 1999a) before strong earthquakes. The present paper is dedicated to the electric-photochemistry mechanism of seismoionospheric coupling and to the effects connected with the presence of "external electric sources" in the lithosphere, lower atmosphere or the lower D region of the ionosphere. Several experimental facts attract the attention to this mechanism of seismoionospheric coupling. First, there are observations of the reverse of the sign of near-ground vertical electric field before strong earthquakes (Mikhailov et al., 2003; Rulenko, 2000). Second, there are very similar quasi-harmonic variations in the near-ground electric field and the

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intensity of the "atmospheric noise" reported in Mikhailov et al. (2004). And, finally, there is the "blooming" of the ionosphere for the electromagnetic waves before strong earthquakes (Gokhov et al., 2003). In addition, we should mention the observations (Martynenko et al., 2001; Meek et al., 2004; Bragin et al., 1974) of the "abnormal" electric field in the mesosphere which leads to the formulation of the model of the equivalent external current in the range of altitudes 60–65 km as the generalization of the observed (on the basis of the method of "partial reflections") electric fields of the order of a few V/m (Martynenko et al., 2001; Gokhov et al., 2003). This model is rather similar to the model of equivalent external currents in the mesoscale convective systems (Davydenko et al., 2004). The physical nature of the extraordinary fields in the mesosphere could be connected with some instability, such as instability caused by the interaction of charged aerosols with the convective air flow (Polyakov et al., 1990). Note that in accordance with the observations (Meek et al., 2004), this field, or equivalent external current, exists in the mesosphere as a rule, or, more accurately speaking, they it had been revealed in ~70% of the observations, and this phenomenon is not connected with seismoionospheric processes.

In the present paper, the generation of the electrostatic field in the system "lithosphere–atmospehtre–ionosphere" (LAI) by lithospheric electric field and/or external currents placed near the ground and/or in the mesosphere/lower ionosphere is modelled. Electric current in the near-ground region or lithospheric electric field are of the seismoionospheric origin. Namely, near-ground current could be connected with the radon emanation and/or increasing release of charged aerosols before strong earthquakes (Sorokin et al., 2001). In turn, lithospheric electric field could be connected with electromechanical transformers formed in the Earth crust in the process of earthquake preparation accompanied by opening of the cracks (Molchanov et al., 1995). An influence of the generated electric field on the photochemical and ionospheric characteristics in the range of altitudes of the lower ionosphere is searched. 3D model of this mechanism of seismo ionospheric coupling is developed and the results of numerical calculations are discussed. An influence of the excited electric field on the losses of VLF electromagnetic waves in the "Earth–ionosphere" waveguide is considered qualitatively. The model of two external electric sources existing simultaneously in the lower atmosphere or lithosphere and lower D region is proposed first and it is shown that such a model could explain a lot of electric-photochemistry phenomena in the LAI system observed before strong earthquakes.

2. Photochemical and (quasi)electrostatic models

We only briefly outline here the main points of the electrostatic-photochemistry model (see also Grimalsky et al., 2003; Rapoport et al., 2004b). The electric field is determined from the quasistatic equations (Grimalskiy and Rapoport, 2000) generalized in the case of the presence of external current (Sorokin et al., 2001): $\vec{E} = -\vec{\nabla}\varphi$,

$$\frac{\partial}{\partial t}\frac{1}{4\pi}\Delta\varphi + \vec{\nabla}(\widehat{\sigma}\vec{\nabla}\varphi) = \vec{\nabla}\vec{J}_{\text{ext}}, \tag{1a}$$

where $\vec{J}_{\text{ext}}$, φ, and $\widehat{\sigma}$ are external current, electric potential and conductivity tensor, respectively. Using Eq. (1a), it is possible, in principle, to obtain magnetostatic field $\vec{h}$ from the equation

$$\text{rot}\,\vec{h} = \frac{4\pi}{c}(\widehat{\sigma}\vec{E} + \vec{J}_{\text{ext}}), \tag{1b}$$

but in the present calculations we will be interested only in the electric field. The following shape of the spatial distribution of the external current is accepted: in the (lower) ionosphere

$$\vec{J}_{\text{ext}} = J_{\text{ext}}\vec{e}_z ch^{-1}\left(\frac{z - z_{0u}}{\Delta z}\right)\exp\left[-\left(\frac{x - x_c}{\Delta x}\right)^2 - \left(\frac{y - y_c}{\Delta y}\right)^2\right],$$
$$x_c = y_c = 0. \tag{2a}$$

Here Δx, Δy, and Δz are the horizontal (in x-, y-directions) and vertical (in z-direction) scales of the spatial distribution, $\vec{e}_z$ is a unit vector in the vertical direction, z_{0u} is the coordinate of the maximum of the external current and J_{ext} is its amplitude; for the near-ground external current

$$\vec{J}_{\text{ext}} = J_{\text{ext}}\vec{e}_z\exp\left[-\left(\frac{z}{\Delta z}\right)^2\right]\exp\left[-\left(\frac{x - x_c}{\Delta x}\right)^2 - \left(\frac{y - y_c}{\Delta y}\right)^2\right],$$
$$x_c = y_c = 0. \tag{2b}$$

In the case of the presence of external current sources in the lower atmosphere and ionosphere, at the lower ($z = 0$) and upper ($z = z_{\text{UP}} = 150$ km) boundaries of the region where the electric field is computed the values of φ are fixed,

$$\varphi = 0(z = z_{\text{UP}}), \tag{2c}$$
$$\varphi = \varphi_0(z = 0), \tag{2d}$$

where φ_0 is chosen in accordance with the fair weather conditions. If external vertical field is given at the ground level (at $z = 0$)

$$E_z(z = 0) = E_{z0}\exp\left[-\left(\frac{x - x_c}{\Delta x}\right)^2 - \left(\frac{y - y_c}{\Delta y}\right)^2\right], \tag{3}$$

Eq. (3) is used as the lower boundary condition instead of the condition (2d). In the present paper, we calculate electrostatic field using Eq. (1a) with $\frac{\partial}{\partial t} = 0$. Eq. (1a) is solved using Fourier expansion in horizontal directions x, y and finite differences in z-direction. Periodic boundary conditions at the fictitious "walls" are used and the relation $L_x \gg l_x$ is valid, where L_x and l_x are the distance between these "walls" and the characteristic horizontal dimension of the lithospheric or ionospheric external source, respectively. See more details of the electrostatic model in Grimalsky et al. (2003) and Rapoport et al. (2004b).

Variations of the photochemical coefficients and ionospheric parameters are determined, first of all, by the variations of the electron temperature T_e caused by the variations of electric field (Tomko et al., 1980; Rapoport et al., 2004b). Electron collision frequency ν_e is almost directly proportional to the electron temperature T_e; accurately speaking, $\nu_e \sim \theta^{5/6}$, $\theta = (T_e/T_{e0})$, see Martynenko et al. (1996). Index "0" hereafter corresponds to the values in the unperturbed conditions (when $\vec{J}_{ext} = 0$, perturbation of the electric field is absent, and $T_e = T_{e0}$). Electron concentration is determined in the present model using "photochemical approximation" (Gurevich, 1978). The following relation is used for this (Gurevich, 1978):

$$N_e/N_{e0} \approx \sqrt{\frac{(\lambda_0\alpha_i + \alpha_{D0})(1+\lambda_0)}{(\lambda(\theta)\alpha_i + \alpha(\theta))(1+\lambda(\theta))}}, \quad \lambda(\theta) \approx \beta(\theta)/\gamma. \tag{4}$$

Here λ is negative ion to electron concentration ratio, α_i, α_D, β and γ are the coefficients of ion–ion recombination, dissociative recombination, electron attachment and electron detachment from the negative ions, respectively.

3. Results of numerical calculations

3.1. Verification of the model

Numerical calculations show (see also Rapoport, 2004) that in the absence of external current an increase of near-ground conductivity causes a decrease of near-ground and an increase of ionospheric vertical electric field. This coincides qualitatively with the results of Bliokh (1997). As is shown below, in the presence of the external current only in the near-ground region, change of the sign of near-ground vertical electric field could take place, as was observed in Mikhailov et al. (2003). Dependence of the maximum of near-ground (vertical) electric field (in the point $x = y = 0$) on the amplitude of external near-ground electric current is shown in Fig. 1. Hereafter we suppose that the positive direction for the field and current is the direction of the fair weather field (in other words, downward). This dependence in the inhomogeneous system LAI with the external current occupying a restricted region by altitude (near the ground) can be explained qualitatively as follows. Let us consider instead of the real inhomogeneous 3D system LAI, a two-layered 1D system consisting of two resistances

$$R_1, R_2, R_1 \gg R_2. \tag{5a}$$

The first of these resistances corresponds to the lower atmosphere (region 1) and the second to the other part of the atmosphere and ionosphere (region 2). Both of these regions are supposed to be homogeneous. We also suppose that the external current source of the value I_{ext} is placed in the region 1 and conduction currents in the region 1 and 2 are $I_{1,2}$, respectively. Therefore we have

$$I_1 + I_{ext} = I_2, \tag{5b}$$

$$I_1R_1 + (I_{ext} + I_1)R_2 = U_0, \tag{5c}$$

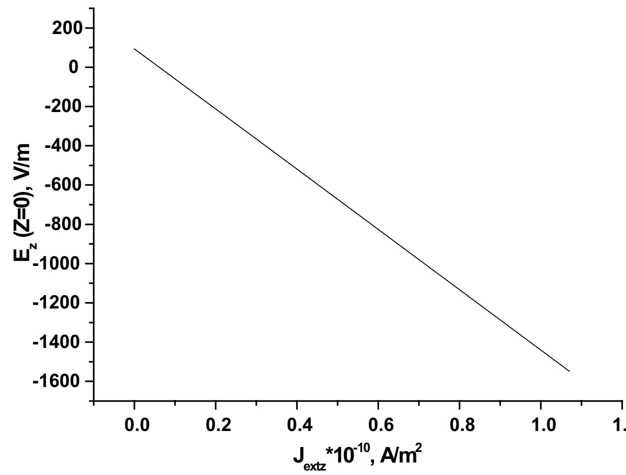

Fig. 1. Dependence of the maximal value of the vertical near-ground electric field (in the point $x = 0$, $y = 0$) on the maximal value of the near-ground external electric current. Positive direction of the electric field and external current coincide with the direction of the fair-weather field (vertically downward). Ratio of conductivities $\sigma(0)/\sigma(60\ \text{km}) = 10^{-4}$; vertical scale of the spatial distribution of external current $\Delta z = 5$ km.

where U_0 is the difference of potentials between the Earth and ionosphere. If $I_{ext} = 0$, then we obtain from Eqs. (5b) and (5c)

$$I_0 = I_1 = I_2 = U_0/(R_1 + R_2), \tag{5d}$$

where I_0 is fair weather current. It follows from Eqs. (5b–d) that

$$I_1 = I_0 - I_{ext}R_2/R, I_2 = I_0 + I_{ext}R_1/R, \tag{5e}$$

$$R = R_1 + R_2. \tag{5f}$$

In accordance with Eq. (5e), if $I_{ext} > 0$ (in other words, I_{ext} is directed in such a way as fair weather current), then $I_1 < I_0$. If I_{ext} is large enough, $I_{ext} > I_0R/R_2 \gg I_0$, then I_1 changes sign as was observed in Mikhailov et al. (2003) and shown in Fig. 1. Note that, to change sign of the near-ground electric field, an external current of order of 10^{-11} A/m^2, in other words, one order larger than the fair weather current is necessary.

3.2. Effects of the two external currents placed near the ground and in the lower ionospheric D region

Fig. 2(b)–(d) illustrate the altitude distributions of the electric field in the different ranges of altitudes (for the day conditions). Corresponding altitude distributions of the external currents and conductivity are shown in Fig. 2(a) and (e), respectively (see figure captions for more details on the parameters used). Note first the negative sign on the few first kilometers of the electric fields E_z (curves 3, 4 in Fig. 2(b)) corresponding to the presence of external currents near the lithosphere (curves 3, 4 in Fig. 2(a)). If the external current near the lithosphere is absent (curves 1, 2 in Fig. 2(a)), the sign of E_z in the same range of altitudes is positive. This corresponds qualitatively to the simplified consideration in Section 3.1, because the amplitudes

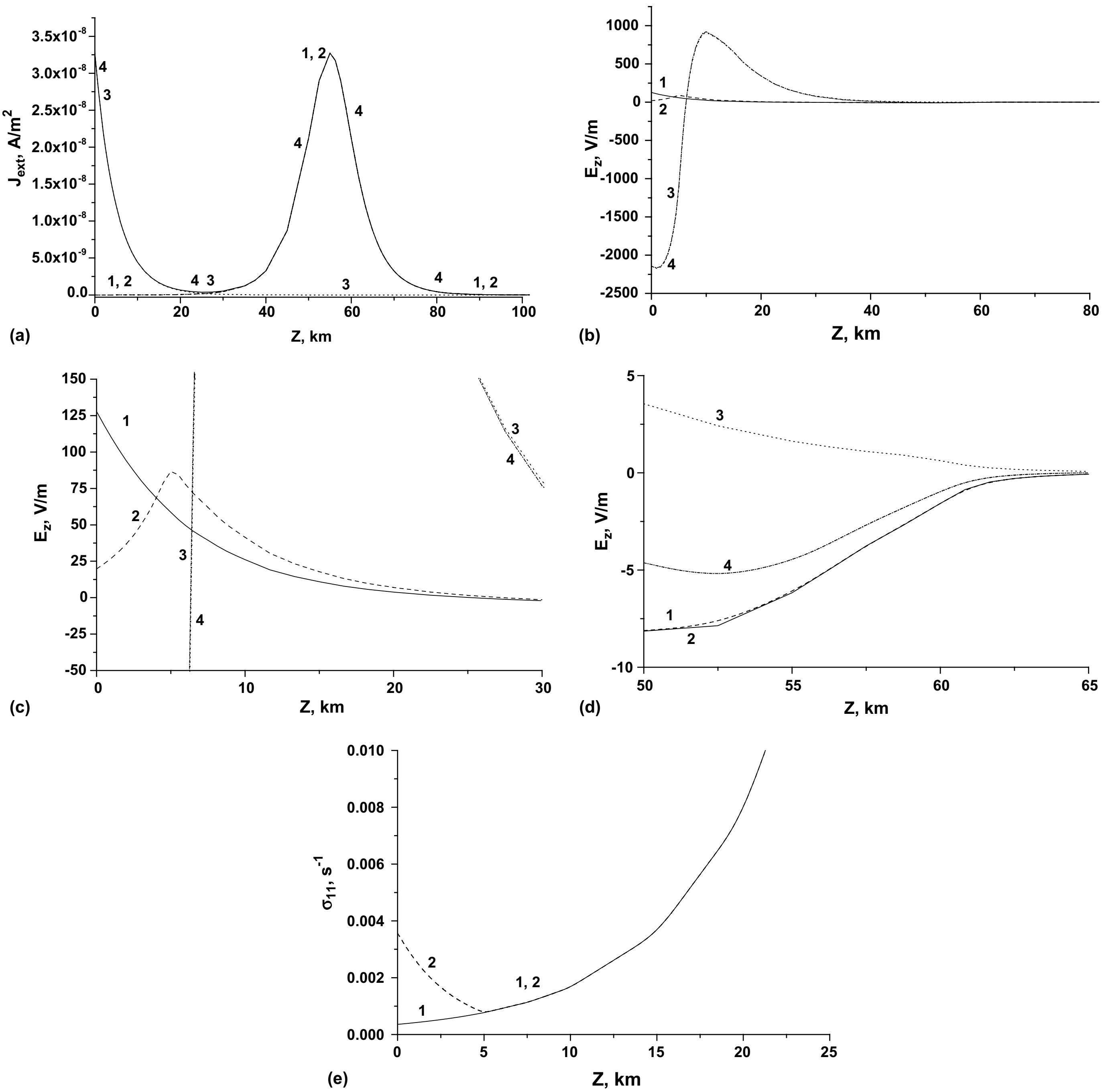

Fig. 2. (a) Dependence of the external current on the altitude, $J_{\text{ext}}(z)$; (1) external current is placed in the mesosphere (with maximum placed at $z = 55$ km), $\sigma(0)/\sigma(z) = 10^{-4}$; (2) external current is placed in the mesosphere (with maximum at $z = 55$ km), $\sigma(0)/\sigma(z) = 10^{-3}$; (3) external current is placed in the near-ground region (with maximum at $z = 0$), $\sigma(0)/\sigma(z) = 10^{-3}$; (4) two external currents are placed in the mesosphere (with maximum at $z = 55$ km) and near-ground region (with maximum at $z = 0$); day conditions, $\sigma(0)/\sigma(z) = 10^{-3}$. (b) Dependence of the vertical component of electric field on the altitude, $E_z(z)$, in the altitude range 0–80 km; curves 1–4 correspond to the curves with the same numbers in (a). (c) The part of (a) in the altitude range 0–30 km. (d) The part of (a) in the altitude range 50–65 km. (e) Dependence of the element of conductivity tensor, σ_{xx}, on the altitude for $z = (0\text{–}25)$ km in the atmosphere and lower ionosphere, isotropic conductivity, $\sigma \approx \sigma_{xx}$; (1) conductivity distribution corresponding to the curve 1 in (a–c); (2) conductivity distribution which corresponds to the curves 2–4 in (a–c). Above the altitude $z = L_\sigma = 5$ km, curve 2 coincides with the curve 1.

of the lithospheric currents near the lithosphere described by the curves 3, 4 in Fig. 2(a) are rather large (of the order of 10^{-8} A/m^2). If the external current in the near-ground region is absent, the peculiarities of the altitude distributions of the E_z in this region (see curves 1, 2 in Fig. 2(b) and (c)) are explained by the corresponding peculiarities of the conductivity distributions (curves 1, 2 in Fig. 2(e)). In particular, curves 1 in Fig. 2(e), (b) and (c) correspond to the exponential growth of the conductivity near the ground (and therefore nonmonotonic altitude distribution) which models the effect of the air ionization due to radon emanation caused by the processes of earthquake prepara-

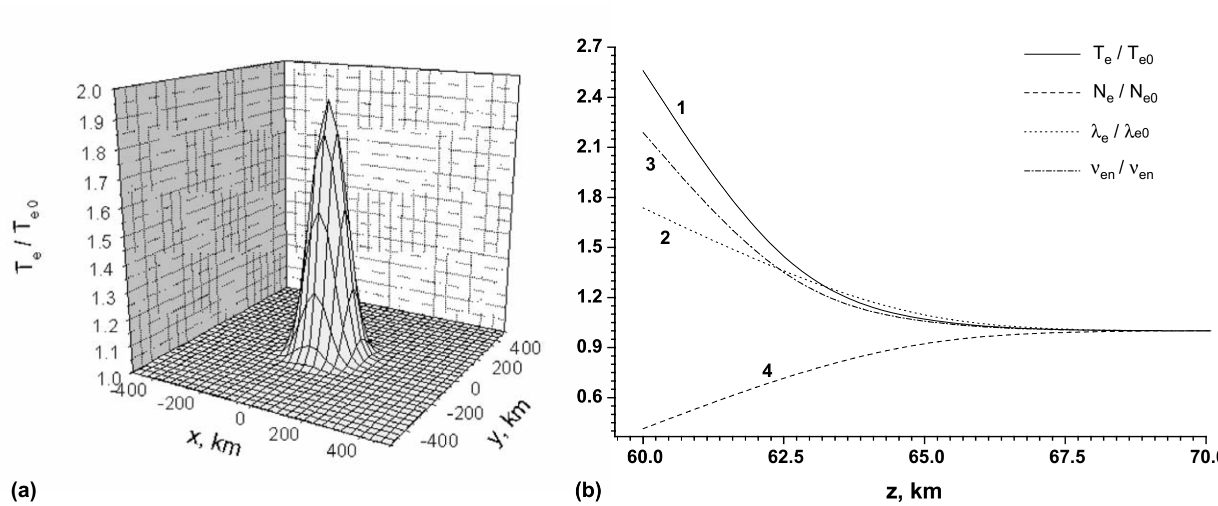

Fig. 3. (a) Spatial distribution of the relative change of electron temperature at $z = 60$ km (at day) corresponding to the curve 4 in Fig. 2(d) (in the presence of external currents *both* near the ground and in the mesosphere). (b) Altitude distribution of the relative change of electron temperature, T_e/T_{e0}, concentration, N_e/N_{e0}, collision frequency, ν_{en}/ν_{en0} and relation of negative ion to electron concentrations, λ_e/λ_{e0} (at day), corresponding to the curve 2 in Fig. 2(d) (in the presence of external current *only* in the mesosphere).

tion (Sorokin et al., 2001). Curves 1 in the same figures correspond to the monotonic growth of the conductivity in the atmosphere and ionosphere. Emphasize the substantial difference in the electric fields in the lower D region (Fig. 2(d)) in the presence of the external current only in the mesosphere (Fig. 2(a) and (d), curves 1, 2), only near the ground (curve 3, Fig. 2(a) and (d)) and both near the ground and in the mesosphere (curve 4, Fig. 2(a) and (d)). As shown in Fig. 2(d), if a strong enough external current exists in the mesosphere independently on the seismoionospheric processes (curve 1 or 2 in Fig. 2(a) and (d)), and then an external current of the same sign appears near the ground (curve 3, Fig. 2(a) and (d)) in the process of earthquake preparation (say, due to the release of charged aerosols and/or emanation of radioactive gases from the Earth crust (Sorokin et al., 2001)), the resulting external current (curve 4, Fig. 2(a)) causes an electric field (curve 4, Fig. 2(d)) that is smaller by the absolute value than the electric field in the absence of the external current near the ground. The reason is that electric fields in the mesosphere/lower D region of the ionosphere caused by the external currents of the same signs placed in the mesosphere and near the ground (curves 1, 2 and 3, respectively, in Fig. 2(d)) have different signs. Therefore the "model of two external currents" proposed in the present paper and in Rapoport (2004) explains at least qualitatively the "blooming" of the ionosphere for the propagating electromagnetic waves before strong earthquakes (Gokhov et al., 2003). This is illustrated by Fig. 3(a) and (b). As seen from these figures, decrease of the absolute value of electric field caused by the appearance of near-ground external current of the seismogenic origin leads to the decrease in electron temperature and electron collision frequency and, at the same time, to the increase in electron concentration. As a result, the losses of the VLF waves in the ionosphere decrease (see also Section 3.4 below). To explain the "blooming" of the ionosphere, in the model (Gokhov et al., 2003) external current in the mesosphere (independent of seismic processes) and we suppose a seismogenic increase of near-ground conductivity. The present model allows not only the inclusion of variations of near-ground conductivity, but also a presence of external currents both in the ionosphere and near the ground. As a result, the present model explains both variations of near-ground electric field and "blooming" of the ionosphere for propagating electromagnetic waves. This is an advantage of the model proposed. Note also that this model predicts considerable values of electric field (of the order of a few V/m, see Fig. 2(d)) and increase in the electron temperature and decrease in electron concentration (up to a few hundred of percents, see Fig. 3(a) and (b)) in the lower ionosphere in the presence of external electric sources. Therefore nonlinear effects in the ionosphere (Gurevich, 1978) could be expected due to electric-photochemistry processes.

3.3. External current in the lower ionospheric D region and (vertical) external electric field in the lithosphere (on the ground)

In the presence of an external current in the lower ionosphere, an appearance of external vertical electric field of the same sign on the ground (Fig. 4(a) and (b)) causes the effect in the lower D region, being analogue to those caused by an appearance of the near-ground external current (Fig. 3(a) and (b)). Namely, electric field (curve 1, Fig. 4(a)), caused by the strong mesospheric external current (curve 4, Fig. 4(a)), in the presence of the lithospheric electric field (the corresponding electric field in the mesosphere/lower ionosphere is described by the curve 2, Fig. 4(a)) decreases in the absolute value (curve 3 in Fig. 4(a)). Fig. 4(b) illustrates the altitude distributions of

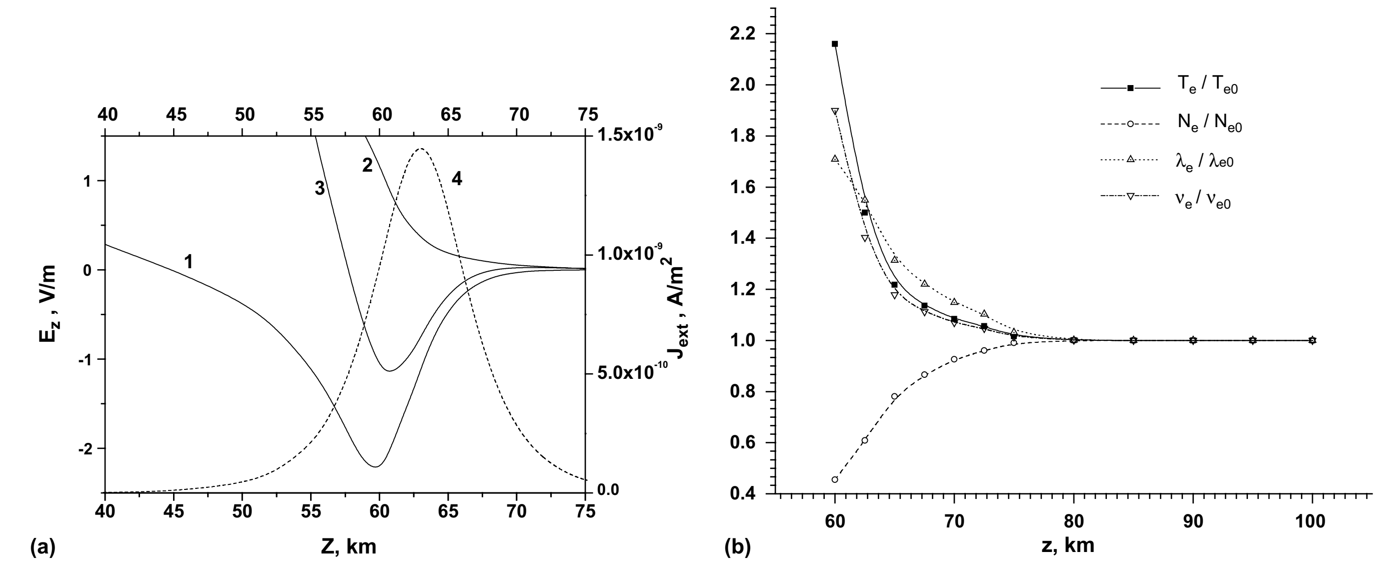

Fig. 4. (a) Altitude distributions of mesospheric external current (curve 4) and vertical electric field, E_z, in the presence of only external current in the mesosphere without external electric field in the lithosphere (curve 1); only external (vertical) electric field in the lithosphere with the amplitude ~1.5 kV/m without external mesospheric current (curve 2); and both external electric field in the lithosphere and current in the mesosphere (curve 3). Night conditions, ratio of conductivities $\sigma(z = 0)/\sigma(z = 60\ \mathrm{km}) = 10^{-3}$. (b) Altitude distribution of the relative change of electron temperature, T_e/T_{e0}, concentration, N_e/N_{e0}, collision frequency, ν_{en}/ν_{en0} and relation of negative ion to electron concentrations, λ_e/λ_{e0}, corresponding to the night conditions in the presence of both external current in the mesosphere (with maximum placed at $z = 63$ km, see (a)) and external vertical electric field with maximum ~1.5 kV/m in the lithosphere.

the relative change of electron temperature, T_e/T_{e0}, concentration, N_e/N_{e0}, collision frequency, ν_{en}/ν_{en0} and relation of negative ion to electron concentrations, λ_e/λ_{e0}, corresponding to the night conditions in the presence of both external current in the mesosphere (with maximum placed at $z = 63$ km) and vertical electric field with maximum ~1.5 kV/m in the lithosphere. In Fig. 5(a) and (b), the spatial distributions in the horizontal plane at the altitude $z = 60$ km of the relative change of electron temperature and electron static conductivity are shown in the presence of only external current in the mesosphere (curve 4 in Fig. 4(a)), respectively. In Fig. 5(c) and (d), the same values in the presence of both ionospheric external current and lithospheric external electric field are shown. We can notice a considerable (of order of 100%) increase in electron temperature and collision frequency (comparatively to the unperturbed condition in the absence of any external current) and decrease (about 60%) in electron concentration, when external electric sources (current and field) are present simultaneously in the mesosphere and lithosphere, respectively (see Figs. 4(a), (b) and 5(c)). In the presence of only mesospheric external current (curve 4 in Fig. 4(a)), the electron temperature increases by more than 3 times as in Fig. 5(a). Relative change of electron conductivity can also reach a considerable value (70–80%) (see Fig. 5(b) and (d)). Therefore detectable influence of electric-photochemical processes on the propagation of electromagnetic (in particular VLF) waves in the waveguide "Earth–ionosphere" could be expected. The increase by about 1.5 times of the static electron ionospheric conductivity determined in the presence of only mesospheric external current (see Fig. 5(b) and curve 4 in Fig. 4(a)), and caused by the appearance of the lithospheric electric field (due to seismogenic processes) (Fig. 5(d)) is demonstrated.

As was shown in Meek et al. (2004) and Martynenko et al. (2001), (external) electric current with the amplitude of order of 10^{-8} A/m^2 exists in the altitude range 60–66 km, and it is important that the sign of this current does not change in this region. At the same time, this sign was not determined in Meek et al. (2004) and Martynenko et al. (2001). In the paper by Bragin et al. (1974), some guideline concerning the sign of the external current in the mesosphere is presented; namely Bragin et al. (1974) presented some results which prove, at least qualitatively, that this sign is negative. In other words the external current is directed vertically upward, in accordance with these data. In Fig. 6(a), altitude distributions of the electric field in the mesosphere in the presence of only mesospheric external electric current of the negative sign (curve 1), only lithospheric external electric field of negative sign (curve 2) and both of these external sources (curve 3) are shown. Altitude distribution of the characteristic electric field E_{ch} (Gurevich, 1978) which shows how effective the electron heating is in the definite electric field (which should be compared with the characteristic field to determine this) is described by the curve 4 in Fig. 6(a). From the comparison of the curves 1–3 with 4, it follows that under considered conditions electron heating is rather effective in the ranges of altitudes 60–70 km. In Fig. 6(b) and (c) the altitude dependences of T_e/T_{e0}, N_e/N_{e0}, ν_{en}/ν_{en0} and λ_e/λ_{e0}, corresponding to the field distributions described by the curves 1–3 in Fig. 6(a), respectively, are shown. Comparison

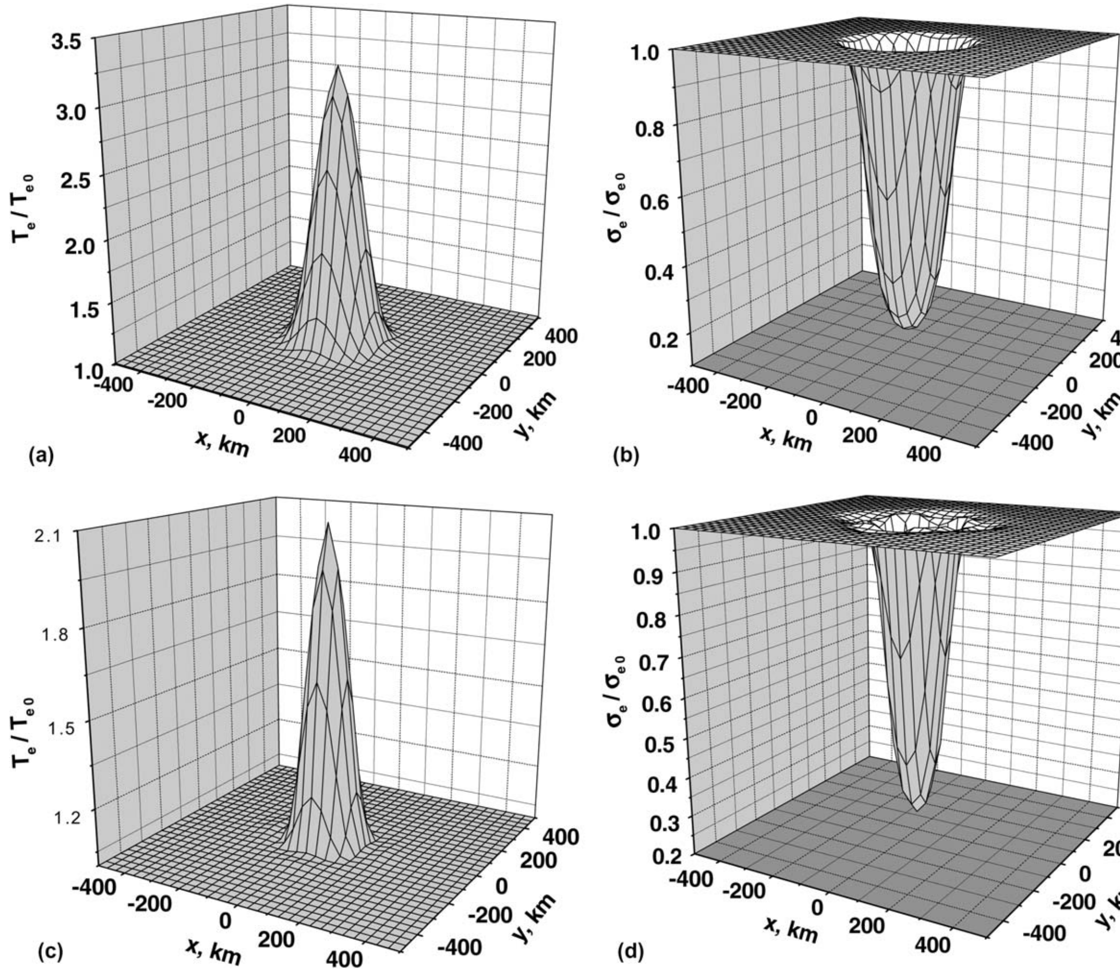

Fig. 5. (a) Spatial distribution of the relative change of electron temperature at $z = 60$ km corresponding in the presence of *only* external current with maximum in the mesosphere (at $z = 63$ km, see Fig. 4(a)); night conditions, relation of conductivities $\sigma(z=0)/\sigma(z=60\ \text{km}) = 10^{-3}$. (b) Spatial distribution of the relative change of static conductivity (due to electron heating) at $z = 60$ km; parameters are the same as in (a). (c) Spatial distribution of the relative change of electron temperature at $z = 60$ km in the presence of *both* external current with maximum in the mesosphere (at $z = 63$ km, see Fig. 4(a)) and external lithospheric electric field (with the maximal value ~1.45 kV/m); night conditions, ratio of conductivities $\sigma(z=0)/\sigma(z=60\ \text{km}) = 10^{-3}$. (d) Spatial distribution of the relative change of static conductivity (due to electron heating) at $z = 60$ km; parameters are the same as in (c).

between, for example Figs. 6(d) and 4(b) shows that the effects on the ionospheric and photochemical parameters of the external positive mesospheric electric current and lithospheric electric field and negative mesospheric electric current and lithospheric electric field are practically the same, if the amplitudes of the corresponding external electric sources are the same.

3.4. Evaluation of the possible effect of external electric sources on the VLF waves propagating in the waveguide "Earth–ionosphere" using "Nonlinear Lorentz Lemma"

We use for these estimations the perturbation theory in the forms of the so-called "Nonlinear Lorentz Lemma" (Rapoport et al. (2004c)) for the field of electromagnetic waves in the waveguide "Earth–ionoshere". In our case, when nonlinearity is not taken into account, we use this relation in its linear form. Let us consider the TM mode with the components H_y, E_z, E_x, where the electromagnetic wave propagates along the x-axis, z is directed vertically upward and we put for simplicity $\frac{\partial}{\partial y} = 0$. Using the method described in Rapoport et al. (2004c) in the linear form, we get

$$\Delta\Phi = \int_{X_1}^{X_2} \Delta k_x(x)\,\mathrm{d}x = -\frac{\omega}{16\pi V_g}\int_{X_1}^{X_2}\left[\frac{\int_{Z_1}^{Z_2}(\vec{F}_E^*\Delta\,\hat{\varepsilon}\,\vec{F}_E)\,\mathrm{d}z}{\int_0^{Z_{\max}}(\vec{F}_E^*\frac{\partial}{\partial\omega}(\hat{\varepsilon}\,\omega)\vec{F}_E + \vec{F}_H^*\vec{F}_H^*)\,\mathrm{d}z}\right]\mathrm{d}x. \tag{6a}$$

Here $\omega = 2\pi f$; f, V_g are frequency and group velocity of the electromagnetic wave, respectively; $\Delta\,\hat{\varepsilon}$, Δk_x, $\Delta\Phi$ are the perturbations (due to the seismogenic processes) of the tensor of dielectric permittivity, the x component of the wave number of the electromagnetic wave and integral change of the complex phase of the wave, respectively; x_1, x_2, z_1, z_2 are the coordinates of the region where the perturbation

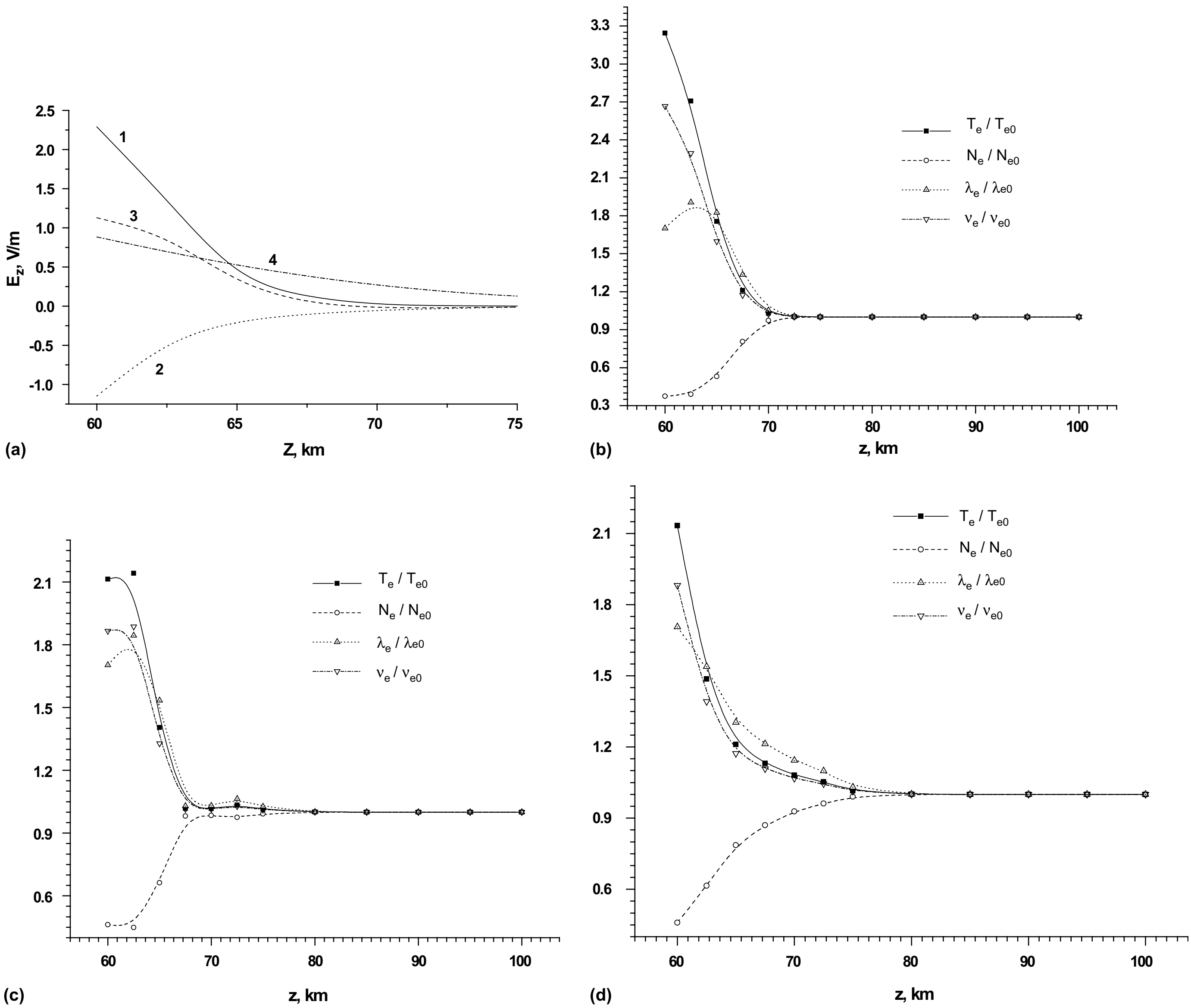

Fig. 6. (a) Altitude distribution of the electric field: (1) in the presence of only external current in the mesosphere with the maximum value $\sim -1.45 \times 10^{-9}$ A/m^2 (equal by the absolute value to those shown in Fig. 4(a), curve 4) placed at $z = 63$ km; (2) only external field in the lithosphere with the maximum value ~ -1.5 kV/m; (3) both external current in the mesosphere and electric field in the lithosphere; (4) characteristic ionospheric electric field E_{ch}. (b) Altitude dependence of the ionospheric parameters corresponding to the curve 1 in (a) and (c) Altitude dependence of the ionospheric parameters corresponding to the curve 2 in (a). (d) Altitude dependence of the ionospheric parameters corresponding to the curve 3 in (a).

of the media parameters takes place, $\Delta x_0 = x_2 - x_1$, $\Delta z_0 = z_2 - z_1$ are the characteristic dimensions of the region of perturbation in the x-, z-directions, respectively; z_{max} is the characteristic width of the equivalent waveguide for the electromagnetic waves; $\vec{F}_{E,H}$ are the functions which describe the polarization of the electric and magnetic field components of the electromagnetic wave, respectively. For the TM mode we have (Vainshtein, 1957)

$$\begin{pmatrix} E_x \\ E_z \\ H_y \end{pmatrix} = \begin{pmatrix} F_{Ex} \\ F_{Ez} \\ F_{Hy} \end{pmatrix} A e^{i(-\omega t + k_x x)} = \begin{pmatrix} \frac{i}{k_0 \varepsilon} k_z \sin(k_z z) \\ -\frac{k_x}{\varepsilon k_0} \cos(k_z z) \\ \cos(k_z z) \end{pmatrix} A e^{i(-\omega t + k_x x)}, \tag{6b}$$

where $k_0 = \frac{\omega}{c}$, A is the amplitude of the electromagnetic wave, and for the simplest rough evaluations, we suppose that inside the waveguide, the tensor $\hat{\varepsilon}$ for VLF waves could be replaced by a homogeneous scalar value $\varepsilon \sim 1$. For an order of magnitude evaluation for VLF electromagnetic waves (Wait, 1996) under the condition $\nu_e \gg \omega$, we get

$$\varepsilon \sim 1 - \frac{\omega_P^2}{\omega(\omega - i\nu_e)}, \quad \Delta\varepsilon \sim \varepsilon'' \sim -i\frac{\omega_P^2}{\omega\nu_e}, \tag{6c}$$

where ω_P is the plasma frequency, ε'' is the imaginary part of ε. In the range of altitudes near $z \sim 63$ km, $|\Delta\varepsilon| \sim (10^{-2}$–$10^{-4})$. Using (6a–c), we get simple approximates

$$\Delta\Phi \sim \Delta k_x \Delta x_0 \sim \Delta k''_x \Delta x_0$$
$$\sim -\frac{\omega}{16\pi V_g}\frac{\Delta z_0}{z_{max}}\Delta x_0 \frac{\Delta\varepsilon}{\varepsilon}, \quad \Delta k''_x = \mathrm{Im}(\Delta k_x), \qquad (6d)$$

which gives under the conditions $f = 5$ kHz (Mikhailov et al., 2003), $z_{max} \sim 70$ km (Wait, 1996), $\Delta z_0 \sim 10$ km, $\Delta x_0 \sim 500$ km: $\Delta k''_x \Delta x_0 \sim 0.05$, what is equivalent to losses of order of 0.5 dB, rather detectable value. Note that in these evaluations we suppose that the process of earthquake preparation occupies rather large region in the Earth crust with the characteristic (horizontal) dimension $\Delta x_0 \sim 500$ km, what is larger than the region used in the calculations in Sections 3.1–3.3 presented above; but for rough estimations we still could use the results obtained above in Sections 3.1–3.3 for such values as ν_e and N_e. To evaluate the effect of the seismogenic processes on the VLF losses, note that in accordance with (6c), for these waves

$$\Delta\varepsilon \sim \varepsilon'' \sim \frac{N_e}{\nu_e}. \qquad (7a)$$

Comparison of Fig. 6(d) with Fig. 6(b), of Fig. 5(c) with Fig. 5(a) or of Fig. 5(d) with Fig. 5(b) (because static conductivity is proportional to the same value as ε'', see Eq. (7a)) leads to the conclusion that an appearance of near-ground external source before strong earthquake leads to the change of VLF losses in the order of at least

$$|\Delta k''_x \Delta x_0| \sim 0.25, \quad \text{if } \Delta x_0 \sim 500 \text{ km}. \qquad (7b)$$

As explained in the Sections 3.2 and 3.3, if appearing external current near the ground or lithospheric external field has a sign opposite to the mesospheric current, seismogenic processes lead to the "blooming" of the ionosphere for the electromagnetic waves propagating above the region of earthquake preparation. If appearing near-ground external electric source has the same sign as those of the mesospheric electric source, this leads to the *increase* in VLF losses. Note that an increase of losses of VLF signal in the lower ionosphere prior to a strong earthquake was recently observed (Shvets et al., 2004).

4. Discussion and conclusions

The advantage of the present model which includes external electric sources both in the mesosphere and in the lithosphere or lower atmosphere is a possibility to explain variations before strong earthquakes of both the near-ground electric field (Mikhailov et al., 2003, 2004) and losses (amplitudes) of electromagnetic waves propagating in the waveguide "Earth–ionosphere" (Gokhov et al., 2003). At the same time, the deeper understanding of the mechanisms of these external sources both in the mesosphere and lower atmosphere/lithosphere (see the physical model of this source in (Sorokin et al., 2001)) needs more theoretical efforts. In particular, the inclusion of the mesospheric source is a result of observations (Martynenko et al., 2001; Meek et al., 2004), and it is not quite clear now how such a mesospheric source appears, while there is some discussion in (Fuks and Martynenko, 2004). The aim of the present paper was the modeling of the electric-photochemistry processes in the presence of given external currents, but not the investigation of the physical nature of the mesospheric external current. Results of these calculations show clearly that possible effect of these external electric sources on the photochemical and ionospheric parameters (such as electron temperature and concentration) are strong enough to provide the remarkable nonlinearity and, may be, some sort of instability (say, electro-heating instability) in the lower ionosphere/mesosphere. This will be a subject of future works.

The following conclusions have been done:

1. If an external current of order of 10^{-8} A/m^2 (at the day conditions) exists in the mesosphere, the appearance of lithospheric electric field with the maximum magnitude of 1.5 kV/m or of a near-ground external current with magnitude of 10^{-8} A/m^2 causes a remarkable decrease of electron temperature and collision frequency, what is in agreement with observations (Gokhov et al., 2003).
2. *The same model* with the presence of *only* the near-ground external current explains observations (Mikhailov et al., 2003) on the change of sign of the near-ground vertical electric field before strong earthquakes. For this, near-ground external current of order of 10^{-11} A/m^2 is enough.
3. We *predict* strong electric field in the (lower) D- region in the presence of external current in the mesosphere *and* near-ground external current or lithospheric electric field. At the same time, increase of near-ground conductivity is taken into account. Consequently, *we make a conclusion* that nonlinear photochemistry-electric processes and, may be, some instabilities in the lower D region (such as, for example. electric-thermal instability) could be possible and such a possibility should be searched for. At day, larger value of external current is necessary than at night, to provide the same value of electric field in the lower ionosphere.
4. We *predict* detectable variations of VLF losses in the "Earth–ionosphere" waveguide before strong earthquakes. In the *presence* of a mesospheric external current, the appearance of the near-ground external current or lithospheric electric field of a sign opposite to the mesospheric current leads to the "*blooming*" (decrease in losses) of the ionosphere for the VLF waves, if external sources are strong enough (see item 1 of the present conclusions) and earthquake preparation region occupies large enough region in the Earth crust. If appearing near-ground external electric source has the same sign as those of the mesospheric electric source, this leads to the *increase* in VLF losses.

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