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On a possible seismomagnetic effect in the topside ionosphere

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Abstract

In this paper we present the results of the computation of the electric and magnetic fields produced in the ionosphere by the near-earth seismogenic disturbance in the vertical atmospheric electrostatic field under different ionospheric conditions. It is shown that in the night-time ionosphere during solar minimum and inside large-scale plasma bubbles, the magnitude of the transverse electric field can attain ∼0.2 and 1.0 mV/m, respectively. The seismomagnetic effect with the magnitude of ∼13 pT is predicted in the topside daytime and night-time ionosphere at any solar activity.

Keywords: Earthquake precursor; Ionosphere; Electrostatic field; Seismomagnetic effect

1. Introduction

There are numerous publications which provide the observational evidence of pre-earthquake ionospheric perturbations (e.g., Pulinets and Boyarchuk, 2004, and references therein; Oyama et al., 2008, 2011; Liu et al., 2009, 2010, 2011; Sharma et al., 2010; Le et al., 2011; Ryu et al., 2014). However, the question if these perturbations are really associated with seismic activities preceding earthquakes remains unresolved (Rishbeth, 2006). It is mainly because of ionospheric variability (over time-scales from hours and days to solar cycles) caused by solar and magnetospheric influences as well as by impact of lower atmosphere (e.g., Prölss, 1995; Rishbeth, 1991; Forbes et al., 2000; Rishbeth and Mendillo, 2001; Mendillo et al., 2002; Zhang and Holt, 2008). Furthermore, physical mechanisms for pre-earthquake seismo-ionospheric coupling are still far from being clearly understood. In the literature, a number of probable drivers responsible for precursory seismo-ionospheric effects have been discussed (e.g., Hayakawa, 1999, 2000; Hayakawa and Molchanov, 2002). One of them is the seismogenic electrostatic field (SEF) that could be seen near the Earth's surface as a perturbation in the vertical atmospheric electrostatic field E_z. Perturbations in E_z have been observed prior to several earthquakes within their preparation zones (Kondo, 1968; Vershinin et al., 1999; Hao et al., 2000; Kamogawa et al., 2004). Before strong earthquakes, the magnitude of E_z perturbation can reach 300–1000 V/m. Hao et al. (2000) have found that the pre-earthquake E_z perturbation's lateral scale size R_0 is related to the imminent earthquake magnitude M as $R_0 \sim \exp(M)$, where R_0 is taken in kilometers. Thus, for major earthquakes with $M \sim 8$, a value of R_0 can be assumed to be as large as ∼3000 km. It is presently unclear what is underlying mechanism for SEF. There has been made an attempt to explain

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generation of SEF by electric currents associated with the stressed rock (Freund, 2000, 2010; Freund et al., 2004, 2009; Freund and Sornette, 2007). Under certain conditions, SEF can penetrate into the ionosphere and modify ionospheric plasma density (e. g., Pulinets and Boyarchuk, 2004; Kuo et al., 2011, 2014; Liu et al., 2011). In contrast, penetration of SEF into the ionosphere is negligibly small according to Denisenko et al. (2008) and Ampferer et al. (2010). Another plausible mechanism for pre-earthquake electric field appearance in the ionosphere was suggested by Oyama et al. (2011) and Sun et al. (2011) who presumed that the electric field could be generated in the ionospheric E layer dynamo region (around the height of 100 km) due to the atmospheric gravity wave which might be induced by the pre-earthquake seismic activity.

In this report, we calculate the perturbations in the electric and magnetic fields, which might be produced by SEF in the ionosphere under different ionospheric conditions.

2. Basic equations

The penetration of SEF into the ionosphere is modeled following the similar formalism to that used by Park and Dejnakarintra (1973) to examine the mapping of thundercloud electrostatic fields into the ionosphere. Under steady state conditions, the governing equations are

$$\nabla \cdot \mathbf{J} = 0 \tag{1}$$

$$\mathbf{J} = \boldsymbol{\sigma}\mathbf{E} \tag{2}$$

$$\mathbf{E} = -\nabla\Phi \tag{3}$$

where $\mathbf{J}$ is the electric current density, $\boldsymbol{\sigma}$ is the electrical conductivity tensor, $\mathbf{E}$ and Φ are the electrostatic field and potential, respectively. Neglecting the Earth's curvature, and using cylindrical coordinates (r, φ, z) centered at a forthcoming earthquake epicenter and with the z axis pointing vertically upward, we represent the seismogenic perturbation in the vertical atmospheric field near the Earth's surface by the Gaussian-like spatial distribution

$$\Delta E_z = E_0 \exp[-\ln(10)(r/R_0)^2] \tag{4}$$

where E_0 and R_0 are the peak value and the scale size of electric field perturbation, respectively. If one assumes that the geomagnetic field $\mathbf{B}$ is vertical, and the electrical conductivity tensor depends only on z, the following equation for the electrostatic potential Φ can be obtained from (1)–(3)

$$\partial^2\Phi/\partial^2 r + (1/r)\partial\Phi/\partial r + (1/\sigma_p)\partial(\sigma_0\partial\Phi/\partial z)/\partial z = 0, \tag{5}$$

where σ_p is the Pedersen conductivity, and σ_0 is the specific conductivity. At altitudes below 70 km, the conductivity is isotropic ($\sigma_0 = \sigma_p$) since the geomagnetic field does not affect drifts of charged particles. Above 70 km, the presence of the geomagnetic field results in the anisotropy of the conductivity ($\sigma_0 \neq \sigma_p$). The Eq. (5) can be solved analytically if the conductivities σ_0 and σ_p depend exponentially on altitude. In the case of isotropic conductivity (setting $\sigma_0 = \sigma_p = b \exp(z/h)$ where b and h are constants), we obtain

$$\Phi = \int_0^\infty J_0(kr)[A_1(k)\exp(c_1 z) + B_1(k)\exp(c_2 z)]dk \tag{6}$$

where J_0 is the zero-order Bessel function of the first kind, A_1 and B_1 are coefficients, $c_1 = -1/(2h) - [1/(4h^2) + k^2]^{1/2}$, $c_2 = -1/(2h) + [1/(4h^2) + k^2]^{1/2}$.

For the anisotropic region, where $\sigma_0 = b_0 \exp(z/h_0)$ and $\sigma_p = b_p \exp(z/h_p)$, the solution to Eq. (5) is

$$\Phi = \int_0^\infty J_0(kr)[A_2(k)I_\nu(kf) + B_2(k)K_\nu(kf)]f^\nu dk \tag{7}$$

where J_ν and K_ν are the ν-order modified Bessel functions of the first and the second kind, respectively, A_2 and B_2 are coefficients, $\nu = h_p/(h_p - h_0)$, $f = 2\nu h_0(b_p/b_0)^{1/2}\exp[-z/(2\nu h_0)]$.

The coefficients A_1, B_1, A_2, and B_2 are determined from boundary conditions.

The electric field components are given by

$$E_r = -\partial\Phi/\partial r \tag{8}$$

$$E_z = -\partial\Phi/\partial z \tag{9}$$

Since we assume that the geomagnetic field $\mathbf{B}$ is vertical, E_r is perpendicular to $\mathbf{B}$, while E_z is parallel to $\mathbf{B}$.

Above 90 km, the geomagnetic field aligned conductivity σ_0 is sufficiently high and much larger the transverse conductivity σ_p so the geomagnetic field lines of force are nearly equipotential lines for the case of perpendicular electrostatic fields with scale sizes of more than a few tens of kilometers. It makes possible to consider the ionospheric region from ~90 to ~600 km as a thin conducting layer with a geomagnetic field line integrated Pedersen conductivity $\sum_p$. (Note that the local conductivity σ_p is negligible above 600 km.) Thus the continuity equation of electric current can be written at $z = 90$ km in the following form:

$$\sigma_0 E_z = \nabla_\perp\left(2\sum_p \mathbf{E}_\perp\right) \tag{10}$$

where $\nabla_\perp$ denotes the gradient operator in the two dimensions transverse to $\mathbf{B}$, the factor 2 before $\sum_p$ accounts for a contribution of the Pedersen conductivity of the magnetically conjugate ionosphere. Note that the relation similar to (10) was previously used as an upper boundary condition while solving the problem of SEF penetration into the ionosphere by Denisenko et al. (2008) and Ampferer et al. (2010). Eq. (10) is explicitly expressed as

$$\sigma_0\partial\Phi/\partial z = 2\sum_p[\partial^2\Phi/\partial r^2 + (1/r)\partial\Phi/\partial r] \tag{11}$$

Relations (4) and (11) represent the lower and upper boundary conditions, respectively, to evaluate the electrostatic potential Φ.

The magnetic effect of seismogenic electric current is described by the Biot–Savart law, which in our case of