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Vertical coupling between troposphere and lower ionosphere by electric currents and fields at equatorial latitudes

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ABSTRACT

Thunderstorms play significant role in the upward electrical coupling between the troposphere and lower ionosphere by quasi-static (QS) electric fields generated by quiet conditions (by slow variations of electric charges), as well as during lightning discharges when they can be strong enough to produce in the nighttime lower ionosphere sprites. Changes are caused in lower ionosphere by the QS electric fields before a sprite-producing lightning discharge which can play role in formation of the stronger sprite-driving transient QS electric fields due to lightning. These changes include electron heating, modifications of conductivity and electron density, etc. We demonstrate that such changes depend on the geomagnetic latitude determining the magnetic field lines inclination, and thus, the anisotropic conductivity. Our previous results show that the QS electric fields in the lower ionosphere above equatorial thunderstorms are much bigger and have larger horizontal extension than those generated at high and middle altitudes by otherwise same conditions. Now we estimate by modeling the electric currents and fields generated in lower ionosphere above equatorial thunderstorms of different horizontal dimensions during quiet periods and of their self-consistent effects to conductivity whose modifications can play role in formation of post-lightning sprite-producing electric fields. Specific electric currents configurations and distributions of related electric fields are estimated first by ambient conductivity. Then, these are evaluated self-consistently with conductivity modification. The electric currents are re-oriented above ~85 km and flow in a narrow horizontal layer where they dense. Respectively, the electric fields and their effect on conductivity have much larger horizontal scale than at middle latitudes (few hundred of kilometers). Horizontally large sources, such as mesoscale convective structures, cause enhancements of electric fields and their effects. These modified features may affect production of sprites.

1. Introduction

Coupling between different atmospheric regions of the Earth includes not only downward influences, but also ones transmitted from its lower to upper regions. Upward electrical coupling takes place between troposophere and lower ionosphere and is realized within the global atmospheric electrical circuit (Rycroft et al., 2000, 2008, 2012a,b; Williams, 2009, etc.) by the electrical sources located in the troposphere – thunderstorms (TS), meso-scale convective systems and complexes (MCS and MCC), and electrified shower clouds (ESC) (MacGorman and Rust, 1998). The concept of GEC emanates from the Wilson's hypothesis (Wilson, 1921) of the formation of the ionospheric electric potential V_I (V_I=250–300 kV with respect to the Earth's surface) as a result of the conduction currents **j** flowing from the tropospheric electrical sources (TS, ESC, etc.) upward into the lower ionosphere. The upward coupling between the troposphere and lower ionosphere is exhibited by the transient luminous events and other phenomena in the lower ionosphere. Sprites (Sentman et al., 1995, Lyons, 1996) produced by quasi-static (QS) electric fields generated at night after positive cloud-to-ground (+CG) lightning discharges (typically) are the brightest demonstration of such coupling. The discovery of sprites (Franz et al., 1990) gave rise to more intense investigations of the considered type of coupling, in contrast with the earlier period when some authors have considered the lower ionosphere as an'ignorosphere' (Sechrist, 1974). The sprites are elements of the global electrical circuit (Rycroft et al., 2007) and possibly affect the chemistry (the balance of small constituents) in meso- and stratosphere; therefore, conditions of their production are of interest. The research problems concerned to sprites, the sprite-producing lightning discharges and related electric fields have been considered in the first book on sprites (Rycroft, 2006).

Many studies have been devoted to modeling of the quasi-

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steady and transient quasi-static electric currents **j** and fields **E** generated by tropospheric electrical sources or by ground sources (e.g. related to earthquakes) on local and regional scales, as well as to global-scale models of interaction of tropospheric electrical sources with GEC. For example, Kartalev et al. (2004, 2006), and Rycroft et al. (2005) represented model studies of the global-scale effects of thunderstorms on the ionospheric potential and on the ionospheric electric currents with the account of the geomagnetic latitude and the influences the anisotropic conductivity above 70 km. Most recently, a global-scale time-dependent model was proposed for the response of GEC to lightning discharges (Jansky and Pasko, 2014).

A series of local-scale models for the penetration of DC electric fields in the ionosphere generated from ground sources were developed, as well. Pasko et al. (1998) developed a self-consistent model for the steady-state electric fields in the lower ionosphere above a thunderstorm with account to the electron heating, conductivity and electron density modifications caused by these electric fields **E** at night. Recently Ampferer et al. (2010) and Denisenko et al. (2013) proposed models for penetration of quasi-steady electric fields **E** from ground electric sources in the highly conducting ionosphere and accented on the principal problem of high sensitivity of results to the model boundary conditions. These authors obtained that, depending on the choice of model upper boundary condition in the ionosphere, the computed values of the ionospheric electric fields could differ by two orders of magnitude or even more. By a choice of physically adequate boundary conditions Ampferer et al. (2010) and Denisenko et al. (2013) obtain that the studied electric fields cannot penetrate into the ionosphere (they are too small). Their main conclusions (high sensitivity of the ionospheric electric fields to boundary conditions, which determines, by adequate boundary conditions, their rapid decrease with their penetration into the ionosphere) actually coincide with those obtained by Velinov and Tonev (1995) and Tonev (2007). The mentioned local-scale models are 2D models by which is recognized the strong influence on **E** of the anisotropic ionospheric conductivity and of its rapid increase with the altitude. However, the mentioned (and many other) models use the assumption that the geomagnetic field **B** is vertically oriented, i.e. the inclination of its field lines is $I = \pm 90°$. This inclination corresponds to the polar regions and, hence, the assumption $I = \pm 90°$ cannot be used in models which consider cases of tropical and equatorial latitudes where is the majority of big thunderstorms. On the other hand, the magnetic field orientation is determinative for the conductivity tensor, and therefore, for the characteristics of the electric fields at altitudes above ~70 to 80 km. This determines necessity of models appropriate by $|I| < 90°$. On the other hand, little attention has been paid on this necessity until now.

The model developed by Tonev and Velinov (2002, 2003) and Tonev (2007) concerns the troposphere–ionosphere electric coupling at equatorial geomagnetic latitudes where the magnetic field is horizontally oriented ($I = 0°$). According to their results (discussed further in this work, as well) the distributions of the electric field in the lower ionosphere above a thundercloud has several specific features and is much larger than that obtained by vertical geomagnetic field orientation. The reason is that at equatorial latitudes the electric field **E** from a thunderstorm and the magnetic field **B** are mutually transverse, as opposed to the case of vertical geomagnetic field. Tonev and Velinov (2002, 2003) and Tonev (2007) reveal also that the electric field distributions above equatorial thunderclouds is characterized by a horizontal offset of tens of kilometers from the source, and have big horizontal dimensions. However, the model uses the idealized assumption for constant conductivities, and does not take into account the self-consistent dependence of the ionospheric conductivity with the electric field applied caused due to the electron heating and conductivity. Here we consider the effects in the equatorial lower ionosphere caused by electrified cloud structures of different horizontal scale – from a single cell to large structures such as mesoscale convective systems (MCS). The electric fields and the modifications of the conductivity caused by them are estimated self-consistently. A 3D numerical model of the self-consistent variations of the electric field and conductivity is proposed based on the continuity equation for the electric current **j**. It is described in Section 3 together with the numerical algorithm used to compute the solutions. We found that the region of significantly reduced conductivity in the layer 70–95 km has large horizontal dimensions (few hundred kilometers).

This effect, as well as the factors of the local geomagnetic field orientation, the large total charge in the source electrified cloud structure, and its specific distributions, lead to dramatic enhancement of the electric fields in the lower ionosphere. Peculiarities of the electric current and field distributions are discussed to explain the results. These peculiarities are of importance for better understanding the behavior of the global atmospheric electrical circuit.

2. Relations between geomagnetic and electric fields and conductivity

Representations in this section and further are based on the theory of the ionosphere electrodynamics (Rishbeth and Garriott, 1969; Kelley, 2009). The atmospheric conductivity σ increases quasi-exponentially with altitude between the surface and the ionosphere. In the lower ionosphere and above it is a characteristic of large (mainly diurnal) variability due to different factors. At ionospheric heights where the effective electron–neutral collision frequency ν_{en} is smaller than the electron gyro-frequency ω_e (above $Z_I = 70$ km under undisturbed conditions) conductivity is affected also by the geomagnetic field **B**; it is anisotropic there and is represented by a tensor $[\sigma]$. Below 70 km, where $\nu_{en} > \omega_e$, the conductivity σ is a scalar. At altitudes of anisotropic conductivity $z > Z_I = 70$ km the relationship between the electric field **E** and current density **j** is given by the Ohm's law $\mathbf{j} = [\sigma']\mathbf{E}$ where $[\sigma'] = \begin{bmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix}$ in Cartesian coordinates (x',y',z') where axis z' is parallel to the magnetic field **B**, axis y' points to the geomagnetic south, and axis x' completes the Cartesian system of coordinates. σ_0, σ_P and σ_H are the field-aligned, Pedersen and Hall conductivity components expressed as follows:

$$\sigma_0(z) = \frac{e^2 N_e}{m_e \nu_{en}} \tag{1a}$$

$$\sigma_P(z) = N_e e^2 \left(\frac{\nu_{en}}{m_e\left(\nu_{en}^2 + \omega_e^2\right)} + \frac{\nu_{in}}{m_i\left(\nu_{in}^2 + \omega_i^2\right)} \right) \tag{1b}$$

$$\sigma_H(z) = N_e e^2 \left(\frac{\omega_e}{m_e\left(\nu_{en}^2 + \omega_e^2\right)} - \frac{\omega_i}{m_i\left(\nu_{in}^2 + \omega_i^2\right)} \right) \tag{1c}$$

Here N_e and N_i are the electron density, ν_{in} is the effective ion-neutral collision frequency, ω_i is the ion gyro-frequency, e and m_e are the charge and mass of the electron, m_i is the effective ion mass. Under dynamic conditions realized by thunderstorm electric fields the Hall conductivity σ_H remains an essential component