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EFFECTS IN EQUATORIAL LOWER IONOSPHERE CAUSED BY ELECTRIC FIELDS FROM TROPOSPHERIC SOURCES

Peter Tonev

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: ptonev@bas.bg

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Abstract: *Effects of the quasi-DC electric fields in the lower ionosphere above electrified clouds and thunderstorms at equatorial geomagnetic latitudes are studied, related to electron heating and modification of conductivity above 60 km. Numerical modeling of the self-consistent behavior of the electric fields and conductivity is developed based on the continuity equation for the electric current. The model results show significant reduction (up to 7-8 times) of the ionospheric conductivity.*

ЕФЕКТИ В НИСКАТА ЕКВАТОРИАЛНА ЙОНОСФЕРА ПРИЧИНЕНИ ОТ ЕЛЕКТРИЧЕСКИ ПОЛЕТА ОТ ТРОПОСФЕРНИ ИЗТОЧНИЦИ

Петър Тонев

Институт за космически изследвания и технологии – Българска академия на науките
e-mail:ptonev@bas.bg

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Резюме:. *Effects of the quasi-DC electric fields in the lower ionosphere above electrified clouds and thunderstorms at equatorial geomagnetic latitudes are studied, related to electron heating and modification of conductivity above 60 km. Numerical modeling of the self-consistent behavior of the electric fields and conductivity is developed based on the continuity equation for the electric current. The model results show significant reduction (up to 7-8 times) of the ionospheric conductivity.*

Introduction

Structures containing electrical charges in the lower troposphere, such as separated thunderstorms, mesoscale convective systems, squall lines, hurricanes, etc., are the main tropospheric sources of strong quasi-electrostatic fields in the middle atmosphere and lower ionosphere. These electric fields of long duration (hours) can cause effects in the lower ionosphere above them concerned to electron heating: changes of physical characteristics, such as electron, ion and neutral temperatures, electric conductivity, parameters responsible for ionization balance, etc. Another possible source of quasi-electrostatic coupling between troposphere and lower ionosphere can be earthquakes. This type of coupling is latitude-dependent due to the sensitivity of electric currents and fields to geomagnetic (gm) field above 70 km. Our previous studies show that by horizontally oriented gm field (at equatorial gm latitudes) a compact tropospheric source generates much stronger electric fields in the lower ionosphere (resp. more exaggerated effects) than at higher gm latitudes under similar conditions. This is because the electric fields at 70-110 km are predominantly vertically oriented, but while the field-aligned conductivity is responsible for them at high latitudes, the much smaller Pedersen conductivity is the factor at the gm equator. Here we study the effect of conductivity change in night-time lower ionosphere at gm equatorial latitudes caused by mesospheric convective system with a large total electric charge. This goal is achieved by modeling the DC electric fields (by Maxwell equations) self-consistently with conductivity variations caused by these fields. Another possible effect is heating of the neutral atmosphere by few degrees. It is also demonstrated a highly unsymmetrical distribution of this effect in space, and its significant shift to the east. The conductivity variations studied are indirectly responsible for generation of intensification of the electric fields in equatorial ionosphere above 90 km; these are much larger than those at higher latitudes. As a result, at gm equatorial latitudes there will be better conditions for realization of sprites: actually, this is supported by observations.

Influence of electric fields on ionospheric conductivity

Investigations of the quasi-DC electric fields **E** generated by tropospheric electric source of small-scale (single thunderstorms - TS) or mesoscale (e.g. mesoscale convective systems) in lower ionosphere are of interest due to different effects caused by these fields, such as electron heating, excitation of molecules, formation of streamers and sprites [1, 2], etc. The electric conductivity σ (which is isotropic below 70 km, and anisotropic above) is one of the characteristics sensitive to the electric field **E**. Since in the ionosphere σ influences **E**, in its turn, both characteristics $[\sigma]$ and **E** have to be evaluated self-consistently.

Conductivity is performed by electrons and ions: $\sigma = \sigma_e + \sigma_i$, where σ_e and σ_i are the electron and the ion conductivities. The electron conductivity σ_e is the only component of σ which is sensitive to the applied electric field **E**; it becomes important above 60 km. The effect of electric field **E** on σ_e arises when the electric field intensity is large enough, i.e. by $|\mathbf{E}|N_0/N > E_M = 1620$ V/m, where N is the neutral atmosphere density, and N_0 is its density at the sea level [1]. In the last case σ_e decreases due to the reduction of electron mobility m_e, since $\sigma_e = q_e N_e \mu_e$ (N_e is the electron density, q_e is elementary charge). The following relation (Fig.1) between electric field intensity **|E|** and σ_e takes place [1]:

(1a) $$\log(\mu_e N) = 50.97 + 3.026\log(y) + 0.084733\left(\log(y^2\right) \qquad \text{by } yN_0 \geq 1620 \text{ V/m};$$

(1b) $$\mu_e = \mu_{e0} = 1.36\, N_0/N \qquad \text{by } yN_0 < 1620 \text{ V/m}, \qquad \text{where } y = |\mathbf{E}|/N.$$

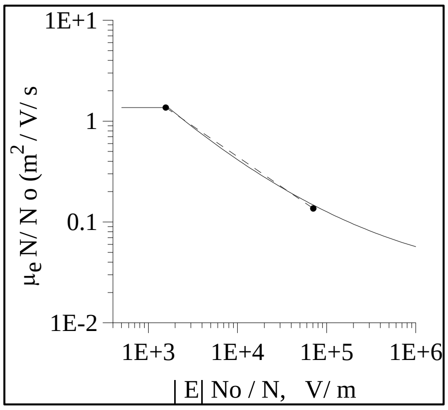

Fig. 1. Electron mobility μ_e as a function (1) of intensity of the electric field **|E|** applied (solid curve). A simple approximation valid by **|E|** N_0 / N < 70 kV/m is shown by a dashed line.

The decrease of σ leads to a self-consistent increase of **|E|**. N is adopted from *MSIS-E-90* (http://modelweb.gsfc.nasa.gov/models/msis.html) used for equatorial latitude at night for moderate solar activity. The conductivity above altitude z = 70 km is anisotropic (presented by a tensor $[\sigma]$) and becomes sensitive to the geomagnetic field **B** and its local orientation. Its components σ_0, σ_P, and σ_H (the field-aligned conductivity and conductivities of Pedersen and Hall) are known functions of the electron density N_e and on electron-neutral ν_{en} and ion-neutral ν_{in} collision frequencies:

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

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

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

Here m_e and m_i are the electron mass and average ion mass; $\omega_e = 2.992\times10^{10}|\mathbf{B}|\ \mathrm{s}^{-1}$, $\omega_i = \omega_e m_e / m_i$ are the electron and ion gyro-frequencies: their profiles for our calculations are obtained for geomagnetic field magnitude $|\mathbf{B}|$ in nT at gm coordinates (0°N, 30°E) in height interval 60 - 120 km from IGRF2000 used at http://williams.best.vwh.net/magvar.htm. ν_{en} in (2) enhances when $|\mathbf{E}|$ increases above $E_M N/N_0$: it is reciprocal to μ_e. Hence, σ_0, σ_P, σ_H change; they are obtained from (3) with a modified electron collision frequency $\nu_{enM} = \nu_{en}\mu_e(0) / \mu_e(|\mathbf{E}|)$ where μ_e is function of $|\mathbf{E}|$. We use the following undisturbed profiles of conductivities σ_0, σ_P, σ_H above 50 km for night-time conditions:

z, km	50	60	70	80	90	100	110
σ_0, S/m	$5.0^{(-11)}$	$8.0^{(-11)}$	$1.5^{(-9)}$	$8.0^{(-7)}$	$1.2^{(-5)}$	$4.0^{(-4)}$	$2.0^{(-2)}$
σ_P, S/m	$5.0^{(-11)}$	$8.0^{(-11)}$	$1.5^{(-9)}$	$1.6^{(-7)}$	$1.8^{(-7)}$	$2.0^{(-7)}$	$2.1^{(-7)}$
σ_H, S/m	0	0	$1.0^{(-9)}$	$4.5^{(-7)}$	$2.1^{(-6)}$	$4.0^{(-6)}$	$7.0^{(-6)}$

Below 60 km σ is invariable scalar: $\sigma = 2\times10^{-14}$, 3×10^{-12}, 4×10^{-11} at z = 0, 20, 40 km, respectively [1]. The undisturbed profiles of N_e, ν_{en} and ν_{in} correspond to these conductivity profiles according to (2).

3D self-consistent model of DC electric field and conductivity

For the self-consistent study of **E** and $[\sigma]$ the continuity equation is solved for the conduction current $\mathbf{j} = [\sigma]\,\mathbf{E} = \quad \mathbf{E}\nabla\Phi$ with account to conductivity modification expressed by Eqs. (1, 2).

(3) $$\nabla\cdot\mathbf{j} = \quad \nabla\cdot([\sigma]\nabla\Phi) = 0.$$

Here Φ is the potential of **E**. Eq.(3) is solved in Cartesian coordinates (x,y,z) (x points to east; y – to north; z is upward) in domain of altitudes 50-110 km with horizontal distances 0 - y_B by axis y, y_B = 300 km to the north, $x_{BW} = \quad 150$ km (to west), x_{BE} = 400 km (to east). The conductivity tensor $[\sigma]$ is:

(4) $$[\sigma] = \begin{bmatrix} \sigma_P & 0 & \sigma_H \\ 0 & \sigma_0 & 0 \\ -\sigma_H & 0 & \sigma_P \end{bmatrix}$$

Since $[\sigma]$ is function of $|\mathbf{E}|$, Eq.(3) is non-linear. Boundary conditions are:

BC1. At lower boundary z_{LB}= 50 km distributions Φ_{LB} (x,y) and E_{zLB} (x,y) are obtained by the analytical model [4] (since no influence of the geomagnetic field takes place).

BC2. $E_y(y=0) = 0$ due to symmetry of distributions of Φ and **E** related to y=0.

BC3. $\Phi = 0$ at lateral boundaries y_B, x_{BW} and x_{BE}.

Eq. (3) with boundary conditions 1-3 is solved numerically (by multiscale method) and iteratively with respect to the dependence between distributions of **E** and $[\sigma]$ above 60 km.

Features of electric field distributions in lower equatorial ionosphere

Important features of distributions above 80 km of the electric field **E** by tropospheric sources at equatorial gm latitudes are demonstrated in [5, 6] with no account to its sensitivity to the conductivity $[\sigma]$, but they are valid also by conditions considered here. These features are following:

1) The electric current **j** is re-oriented above 80 km from vertical to horizontal (due to Hall conductivity) which flows to east, i.e. $j_x >> j_z$.

2) In height interval 80-100 km at equatorial latitudes the dominating electric field component E_z is much larger than the dominating component E_z at high latitudes (HL) by similar conditions. The reason is that at the equatorial latitudes (EQL), where the eastward current j_x is large, $E_z \approx j_x/\sigma_H$, while at high latitudes $E_z \approx j_z/\sigma_0$, and $\sigma_H << \sigma_0$. In a sample case the ratio between E_z in both cases is:

Altitude z, km	80	85	90	95
E_z(EQL) / E_z(HL)	11.4	27.2	61.5	70.4

With respect to conductivity modifications, the electric fields above 75 km increase self-consistently with the decrease of σ. The ratio E_z(EQL) / E_z(HL) may become even larger due to non-linearity.

3) max E_z at a fixed altitude is significantly shifted horizontally related to the source.
4) The horizontal dimensions of the electric field E are few hundreds of kilometers (asymmetric).

The estimations given above are for a sample case of a centered charge located at altitude 15 km.

A conclusion from 3), 4) is that the meso-scale convective systems with large horizontally distributed charge can generate at 80 - 100 km much larger electric fields than by a single thunderstorm cell, due to the effective superposition.

Ionospheric effect of electric fields by mesoscale convective systems

The effect on the ionospheric conductivity from a meso-scale convective structure with a large total electric charge, Q = 1500 C, is studied by assumption that the charge is uniformly distributed along a straight line of length 100 km with east-west orientation. By such orientation the superposition of electric fields in lower ionosphere will be most effective, according to features 3, 4. The results for the distribution of the DC electric field **E** generated in the lower ionosphere, in a vertical east-west oriented cross-section plain S, are shown in Fig.2. The main characteristics of the electric fields are summarized in the Table. The electric field is large due to cumulation effect for the currents. The horizontal scale, at which E_z is close to its maximum ($E_z > 0.5\, E_{\max}$), is tens of kilometers.

Table. Maximum vertical electric field $E_{z\max}$ at altitudes 70, 85, 95 and 100 km

Altitude, km	75	85	95	100
$E_{\max}$, mV/m	750	57	1.9	0.2
Shift of $E_{\max}$ to East, km	2	34	56	75

The results in Fig.2 can help to explain the large electric fields above a nighttime thunderstorm with several cells observed experimentally [3] at altitude of 95 km. Also, the fact that the red sprites usually appear at distance ten of kilometers far from the causative lightning [2] possibly can be explained by the similar horizontal shift of electric field maximum derived here theoretically.

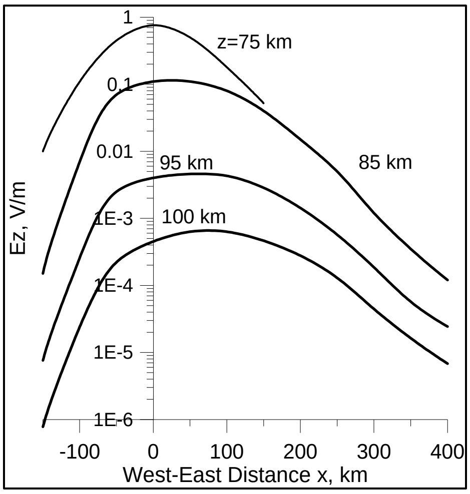

Fig. 2. E_z at different ionospheric altitudes by a mesoscale convective system with total electric charge Q = 1500 C uniformly distributed in a straight line of length 100 km of west-east orientation. E_z is a function of west-east distance x from the center of MCS.

Fig. 3 demonstrates the self-consistent modification of the conductivity field-aligned conductivity σ_0 at altitudes 75, 85, 95, and 100 km in the vertical plain $S_\perp$ across the MCS and transverse to the magnetic field **B** (west-east oriented), as in Fig.2. The results show a significant decrease of conductivity: these variations depend on the altitude z and on the horizontal distance. The maximum change of σ at each altitude is given below:

z, km	75	85	95	100
Max relative change	7.6	5.4	2.0	1.
$x_{\max}$ (horiz. distance)	10	35	65	-

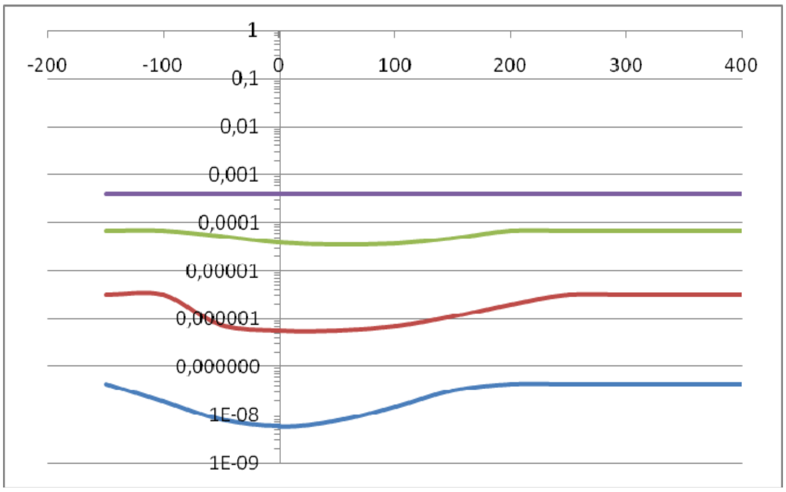

Fig. 3. Modified field-aligned conductivities σ_0 by the elecftric field **E** at altitudes 75, 85, 95, and 100 km, shown as functions of the west-east distance *x* above an MCS. Conditions are the same as in Fig.2.

The conductivity modification is largest at 75 km and absent at 100 km. The horizontal distance, where the effect of conductivity reduction is most significant, increases with the altitude up to tens of km.

Conclusions

The following conclusions are derived from this study:

- A meso-scale convective system at equatorial latitudes with big total charge can generate at night very large quasi-DC electric fields in lower ionosphere: of the order of 1 V/m at altitude 75 km, 0.1 V/m at 85 km, and several millivolt per meter at 95 km.
- The large electric fields are a result of several peculiarities of their distribution: they are characterized with large horizontal extent which is biggest in eastward direction (hundreds of kilometers). The electric field maximum has a horizontal shift by many tens (sometimes, even by few hundreds) kilometers with respect to their source.
- These large electric fields cause significant decrease of the field-aligned conductivity: up to 7.6 times at 75 km; at higher altitudes this effect becomes smaller.

Preliminary analysis shows that the large electric fields thus generated in nighttime equatorial lower ionosphere can cause increase of neutral temperature by few degrees.

It is important to obtain further an estimation whether and in what extent the meso- and larger scale effects in tropical lower ionosphere caused by tropospheric sources influence global processes of the atmopsheric electrical circuit, such as Schumann resonances, etc.

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