On the effect of near-equatorial thunderstorms on the global distribution of ionospheric potential

M.J. Rycroft a, M.D. Kartalev b,*, V.O. Papitashvili c, V.I. Keremidarska b

a CAESAR Consultancy, 35 Millington Road, Cambridge CB3 9HW, UK
b Institute of Mechanics, Bulgarian Academy of Sciences, Acad. G. Bonchev Street, Block 4, Sofia 1113, Bulgaria
c Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109 2143, USA

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Abstract

We develop our earlier attempts to perform an indirect quantitative examination of the hypothesis that electric currents flowing up from thunderstorms to the ionosphere (also known as Wilson currents) charge the ionosphere to a large positive potential with respect to the Earth. First, we take the electrostatic potential arising from the interaction of the solar wind with the Earth’s magnetosphere derived from an experimental data-based model of the high-latitude field-aligned currents. We then obtain the global distribution of ionospheric potential, utilizing a thin shell model, based on integration along field lines of the current continuity equation with a realistic model of ionospheric conductivity. Next, we include additional upward currents to simulate the effect of the three main thunderstorm regions over equatorial Asia/Oceania, Africa and the Americas. We compare the local time variation of the eastward electric field in the ionosphere produced by these three equatorial sources separately, and seek to understand the substantial differences between them. Finally, we examine the variation with local time of the eastward electric field in the ionosphere at low latitudes.

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1. Introduction

One explanation for maintaining the potential of the ionosphere at two or three hundred thousand Volts positive with respect to the Earth’s surface is thunderstorm activity, especially via the thunderstorm currents up to the ionosphere over the main active thunderstorm regions of Africa, Asia/Oceania and America (see, for example, Bering, 1995; Rycroft et al., 2000; Williams, 2002). It is usually assumed that this potential difference drives the downward (air–Earth) currents in the fair weather regions, characterized by typical UT variations, known as the Carnegie curve. Our attention in this study addresses thunderstorms as the basic causative source of this global electric geocapacitor, but it is worth bearing in mind that there are other candidates for this role, such as the gravitational settling of charged heavy aerosols (e.g., Kundt and Thuma, 1999).

A comprehensive quantitative understanding of the global atmospheric electric circuit problem requires appropriate self-consistent modelling of the ionosphere – conducting atmosphere – Earth’s surface system, which has not yet been fully developed to our knowledge. The self-consistency of such a treatment could be provided by an appropriate openness of the applied electrodynamic models of each of these domains to their neighbouring domains. A preliminary step in joining atmospheric electricity phenomena (especially the thun-
derstorm currents) to the global ionospheric electrostatic potential distribution was recently published by Kartalev et al. (2004). This contribution became possible only because of the implementation of a new numerical model of the global distribution of the ionospheric electrostatic potential (Kartalev et al., 2002; Kartalev et al., in preparation). Besides taking as a reference the field-aligned currents over the high latitudes (provided by a data-based model), this model has been modified to accept upward electric currents from the atmosphere, spreading over the global thin shell ionosphere, including the magnetically conjugate ionosphere. A key feature of this treatment is the special role of the region within ±11° of the magnetic dip equator, which, because of the geometry of the field lines, maps to a single line in the procedure of reducing the 3D ionospheric problem to a 2D one. Thus, the upward electric currents generated from the thunderstorms dispersed over hundreds, even thousands, of kilometers, are concentrated into this single line of the 2D ionosphere, essentially contributing to the formation of the equatorial ionosphere current system.

It is noteworthy that the special role of the ±11° equatorial belt was taken into account earlier by some authors who developed ionospheric electrodynamic models, mainly by specifying the boundary conditions on the equator. Thus, Denisenko and Zamay (1992) artificially changed the ratio of the terms in the current continuity equation on the magnetic dip equator. Tsunomura (1999) artificially enhanced one of the terms the conductivity tensor there. Blanc and Richmond (1980) came to the conclusion that for planetary scale calculations the equatorial ionosphere (±11° magnetic latitudes) can be simulated rather simply as a thin wire running along the edge of the planetary dynamo layer. The mathematical closure of the problem costs the artificial introduction of some local time distribution of the conductivity along this thin wire. This approach was found to work satisfactorily, and it is still used in the electrodynamic module of the widely applied Magnetosphere Thermosphere – Ionosphere – Electrodynamics General Circulation Model (MTIEGCM) of Peymirat et al. (1998).

Our treatment of the equatorial ionosphere is developed in detail in Kartalev et al. (in preparation); it was briefly introduced in Kartalev et al. (2004). Here, in Section 2, as a part of the brief description of the global ionospheric electrodynamic model used, we give more details of this equatorial belt approach, which is close (as an idea) to that of Blanc and Richmond (1980).

In Section 3, we consider in more detail, as in the paper of Kartalev et al. (2004), the contribution of thunderstorm activity to the global ionospheric potential. A comparison is made between some consequences of the same thunderstorm inputs, situated mainly within the equatorial ±11° belt, and applied to the America, Africa, or Asia/Oceania regions in the appropriate Universal Time, for the same polar region field-aligned currents and the same solar activity conditions.

2. Outline description of the model

Some basic features of the numerical model of the ionospheric electric potential global distribution used are presented here. Some key model properties were described by Kartalev et al. (2004). A thorough detailed model presentation could be found elsewhere (Kartalev et al., in preparation).

2.1. Geometry of the model

An attempt is made in the model used to resolve the discrepancy between the magnetic field – oriented geometry of the physics of the electrodynamic problem considered and the spherical geometry of the ionosphere – that is the domain where this problem is solved.

The spherical geometry of the 3D ionospheric region considered is shown in Fig. 1, reproduced from Kartalev et al. (2004), presenting a meridional cross-section of the global ionosphere Ω at heights from 90 to 400 km with finite electric conductivity. The existing data-based ionospheric and thermospheric models (MSIS-86 (Hedin, 1987), IRI (Bilitza, 1990)) provide spatial distributions of the ionospheric parameters, needed in the model for Fig. 1. A meridional cross-section of the global ionosphere Ω at heights from 90 to 400 km with finite electric conductivity. The region modelled is limited by the upper and lower ionospheric boundaries and the equatorial magnetic field line $E_nE_2E_{s1}$. The points $E_{n1}$ and $E_{s1}$ are at a magnetic latitude 11° from the equator; $Q_s$ and $Q_n$ are at magnetic co-latitudes of 19° from the geomagnetic poles, limiting the region of closed geomagnetic field lines to larger co-latitudes (i.e., lower latitudes). Reproduced from Kartalev et al. (2004).
computing the spatial conductivities distributions in terms of the spherical coordinates (or, respectively, longitudes, latitudes (colatitudes), heights). The spherical geometry is employed in the model 2D approach, which is over a sphere at a height of 400 km.

In order to present in the most convenient way the electrodynamic problem itself, a coordinate system aligned with the magnetic field is also introduced. In this case, the simplest orthogonal magnetic dipole coordinates $(t, s, \varphi)$ are defined in terms of spherical coordinates $(r, \theta, \varphi)$ as:

$$
t = \frac{r_0 \sin^2 \theta}{r}, \quad 0 \leq \theta \leq \pi,
$$

$$
\varphi = \varphi, \quad 0 \leq \varphi \leq 2\pi,
$$

$$
s = \frac{r_0^2 \cos \theta}{r^2}, \quad 0 \leq \theta \leq \pi,
$$

where $\theta$ is the geomagnetic colatitude, $\varphi$ (azimuth) is the geomagnetic longitude measured eastward from midnight, $r$ is the geocentric distance, and $r_0$ is a fixed geocentric distance.

The geometrical scale factors (sometimes termed Lame coefficients) in magnetic dipole coordinates (see Takeda, 1982) are:

$$
h_t = \frac{r^2}{r_0 \sin \theta (1 + 3 \cos^2 \theta)^2},
$$

$$
h_s = \frac{r^3}{r_0^2 (1 + 3 \cos^2 \theta)^2},
$$

$$
h_\varphi = \frac{r^3 \sin \theta}{r_0},
$$

The unit vectors $(\mathbf{e}_t, \mathbf{e}_s, \mathbf{e}_\varphi)$ associated with the coordinates $(t, s, \varphi)$ are:

$$
\mathbf{e}_t = -\sin \theta \mathbf{e}_r + 2 \cos \theta \mathbf{e}_\theta + \mathbf{e}_z
$$

$$
\mathbf{e}_s = -2 \cos \theta \mathbf{e}_r - \sin \theta \mathbf{e}_\theta
$$

$$
\mathbf{e}_\varphi = \mathbf{e}_\varphi,
$$

where $\mathbf{e}_r, \mathbf{e}_\theta, \mathbf{e}_\varphi$ are the unit vectors, associated with the spherical coordinates $(r, \theta, \varphi)$.

The $(t, s, \varphi)$ coordinates of the magnetic field vector $\mathbf{B}$ and those of its unit vector $\mathbf{b} = \mathbf{B}/B$ are:

$$
\mathbf{B}(0, B, 0), \quad \mathbf{b}(0, 1, 0).
$$

2.2. Current conductivity equation (electrodynamic problem)

The current continuity condition means that the current density $\mathbf{j}$ in the ionosphere satisfies the equation:

$$
\text{div } \mathbf{j} = 0
$$

with Ohm’s law in the ionosphere being taken as:

$$
\mathbf{j} = \sigma_\parallel \mathbf{E}_\parallel + \sigma_p \mathbf{E}_\perp + \sigma_h (\mathbf{b} \times \mathbf{E}_\perp),
$$

where $\sigma, \sigma_p,$ and $\sigma_h$ are the parallel, Pedersen and Hall conductivities, and the indices $\parallel$ and $\perp$ denote vector components parallel and perpendicular to the magnetic field $\mathbf{B}$, respectively; $E_\parallel = \mathbf{B} \cdot \mathbf{E}/B^2, E_\perp = \mathbf{B} \times (\mathbf{E} \times \mathbf{B})/B^2$. In the ionosphere, between 90 and 400 km, $\sigma$ is taken to be infinite, as (for example) Takeda (1982) did.

The electric field $\mathbf{E}$ has two components, namely the polarization field $(\mathbf{E}_p)$ and the dynamo field:

$$
\mathbf{E} = \mathbf{E}_p + \mathbf{U} \times \mathbf{B},
$$

where $\mathbf{U}$ is the neutral gas wind velocity. The ionospheric dynamo fields are not considered further in this present study. A scalar electric potential $\Phi$ is assumed:

$$
\mathbf{E}_p = -\nabla \Phi.
$$

Eq. (6), defined everywhere in $\Omega$, in the dipole coordinates used, reads:

$$
\frac{\partial}{\partial t} (h_t h_s j_t) + \frac{\partial}{\partial \varphi} (h_t h_\varphi j_\varphi) = -\frac{\partial}{\partial s} (h_s h_\varphi j_\varphi),
$$

where the currents densities in the ionosphere are:

$$
j_t = -\sigma_p \frac{h_s}{h_t} \frac{\partial \Phi}{\partial \varphi} + \sigma_h \frac{1}{h_t} \frac{\partial \Phi}{\partial t},
$$

$$
j_\varphi = -\sigma_p \frac{h_t}{h_\varphi} \frac{\partial \Phi}{\partial s} + \sigma_h \frac{1}{h_\varphi} \frac{\partial \Phi}{\partial t},
$$

$$
j_s = -\sigma_h \frac{1}{h_s} \frac{\partial \Phi}{\partial s}.
$$

The 3D problem is then transformed into a 2D one, integrating (10) along the magnetic field line segments, bounded within the region $\Omega$ (Fig. 1). The principal difference from the similar procedure in previous approaches in the literature, based on magnetic field coordinates (e.g., Takeda, 1982), is that in our case this integration is done independently for the segments of the magnetic field line in both hemispheres, distinguishing in this way the magnetically conjugate points, which do not necessarily have the same potential.

Denoting

$$
a = -\sigma_p \frac{h_s}{h_t}, \quad b = -\sigma_p \frac{h_t}{h_\varphi}, \quad c = \sigma_h h_t,
$$

the resultant equation takes the form:

$$
\frac{\partial}{\partial t} (A \frac{\partial \Phi}{\partial t}) + \frac{\partial}{\partial \varphi} (B \frac{\partial \Phi}{\partial \varphi}) + \frac{\partial C}{\partial \varphi} \frac{\partial \Phi}{\partial \varphi} - \frac{\partial C}{\partial t} \frac{\partial \Phi}{\partial t} + \zeta H_2 (f_{t2}^{\text{ext}} + f_{s2}^{\text{ext}} - f_{s1}^{\text{ext}}) = 0,
$$

where $\zeta = -1$ in the northern, and $\zeta = 1$ in the southern, hemisphere.

It is explained in Kartalev et al. (2004) that the current densities at the lower and upper boundaries of the ionosphere have both internal and external parts. The “externally driven” parallel currents $f_{t2}^{\text{ext}}$ flow in the polar regions and are taken from the data-based “external” model (Papitashvili et al., 2001). The “externally
driven” parallel currents $j_{s1}^{\text{ext}}$ are the currents supplied by the thunderstorms. The “internally driven” currents $j_{s2}^{\text{int}}$ are the ionospheric currents, which close in the conjugate ionosphere. Their consideration means the introduction of a new unknown function, as a consequence of which an additional condition is needed to close the problem. In this paper, the current component $j_{s2}^{\text{int}}$ in the North and South is assumed to be generated by the potential difference between a certain ionospheric point $(t, \varphi)$ where the potential is $\Phi$ and its conjugate ionospheric point $(t, \hat{\varphi})$ where the potential is $\hat{\Phi}$.

$$j_{s2}^{\text{int}} = j_{s2}^{\text{int}} = \frac{1}{R_m} (\Phi - \hat{\Phi}), \quad \text{(13)}$$

where $R_m(t, \varphi)$ is the resistance of the magnetospheric flux tube of unit cross-section in the ionosphere. The term $j_{s2}^{\text{int}}$ is zero because the atmosphere is considered to be an insulator.

In the polar regions, we here assume a zero radial “internally driven” current at the upper ionospheric boundary which closes the model.

Eqs. (12) and (13) are solved numerically using an appropriate finite difference scheme (Kartalev et al., 2002). The numerical details are described elsewhere (in Kartalev et al., in preparation). As the computational domain is the whole global thin shell ionosphere, there is no “habitual” boundary problem (say, with boundary conditions on the equator). The “driving forces” here are not the boundary conditions, but the prescribed right-hand sides $(f_{s1}^{\text{ext}}, f_{s2}^{\text{int}})$ in (12). Thus posed, the mathematical problem however does not lead to a unique solution, which reflects the physical non-uniqueness of the potential (but its gradient, i.e., the electric field has a unique solution!). This problem is resolved, simply choosing the value of the potential at some arbitrary point. Note that Nisbet et al. (1978) faced a similar problem, solving also a global potential distribution problem, but in different (spherical) approach. They resolved the problem in similar way, defining the potential of the point at the equator at 06:00 MLT to be zero.

2.3. The equatorial segment

As shown by Kartalev et al. (in press), the transformation of the 3D ionosphere problem to a 2D thin shell problem requires a special treatment of the near-equatorial region – the equatorial belt between $\pm 11^\circ$ latitudes around the magnetic equator (Fig. 1).

It was supposed in that paper that there are no currents flowing from the atmosphere to the ionosphere. The existence of such currents, caused by global thunderstorm activity, was first taken into account, but with some simplifying considerations, by Kartalev et al. (2004). Here, we consider an improved treatment of this near equator problem in the thin shell approach, with atmospheric electric currents flowing up to the ionosphere.

We consider a small volume element of the equatorial belt between $\pm 11^\circ$ latitude around the magnetic equator, enclosed by the surface segments $\Sigma^N(E_{s1}E_{E2}E_{E1})$, $\Sigma^S(E_{s1}E_{E2}E_{E1})$, $\Sigma^E(E_{E1}E_{E2}E_{E1})$, $\Sigma^W(E_{E1}E_{E2}E_{E1})$, $\Sigma^h(E_{E1}E_{E2}E_{E1})$. Applied to this volume element, the current conservation law gives:

$$\int_{\Sigma^N} j_s h_s d\sigma - \int_{\Sigma^W} j_s h_s d\sigma + \int_{\Sigma^E} j_s h_s d\sigma - \int_{\Sigma^S} j_s h_s d\sigma = 0 \quad \text{(14)}$$

The surface integrals over $\Sigma^E$ and $\Sigma^W$ have different signs because of the opposite directions of the outward to the considered volume normal vectors. The same applies for the surface integrals over $\Sigma^N$ and $\Sigma^S$.

It is interesting to estimate the order of magnitude of the terms in (14). Introducing some mean values $h_s, j_s, \hat{\sigma}$ and $h_s$, the division of the whole expression by $j_s d\sigma$, and the assumption of the limit $\delta \sigma \to 0$ gives for the left-hand side of (14):

$$j_s \int_{E_{s1}}^{E_{s2}} h_s ds - j_s \int_{E_{s1}}^{E_{s2}} h_s ds + \frac{\partial \hat{\sigma}}{\partial \phi} \int_{\sigma_{\phi}} h_s ds$$

$$\quad + \hat{\sigma} \int_{E_{s1}}^{E_{s2}} h_s dt \quad \text{(15)}$$

![Fig. 2. Schematic view of a small element of the equatorial belt (between $\pm 11^\circ$ latitude around the magnetic equator).](image)

![Fig. 3. Schematic view of a small element of a non-equatorial ionospheric layer. $Q_1Q_2$ is a segment of a magnetic field line.](image)
The substitution of the quantitative estimates of the integrals in (15) gives:

\[ K^N j^N_i - K^S j^S_i + K^\Phi \frac{\partial j^\Phi}{\partial \varphi} + K^4 j^4_i, \]  

(16)

where \( K^N \) and \( K^S \) are of the order of the ionospheric height and thickness (in km, \( K^N \sim K^S \sim r_2 - r_1 \sim 400 - 90 \sim 300 \) km tunnel); \( K^4 \) is of the order of the distance \( E_{\parallel}E_{\perp} \) in Fig. 2 (the width of the equatorial tunnel). \( K^4 \sim E_{\parallel}E_{\perp} \sim 2600 \) km; the term corresponding to the current flux across the tunnel cross-section is much larger: \( K^\Phi \sim K^N \times K^4 \). These estimates express the specific anisotropy characterizing the equatorial belt, which is reduced to just one line in the thin shell approach.

For a comparison and better understanding of the specific nature of the equatorial line in the 2D approach, it is worth considering another small volume element of the 3D ionospheric layer (Fig. 3).

A relation of the type (14) is valid for the small volume in Fig. 3. Note that the limits \( \delta \varphi \to 0 \) and \( \delta t \to 0 \) give exactly the relation (10), integrated over \( Q_1Q_2 \). In order to make an estimate, analogously with (16), we divide this relation by \( h_o h_i d\varphi dr \) and, taking the limits \( \delta \varphi \to 0 \) and \( \delta t \to 0 \), obtain:

\[ \frac{\partial j^I_i}{\partial t} \int_{Q_1}^{Q_2} h_o ds + \frac{\partial j^\Phi}{\partial \varphi} \int_{Q_1}^{Q_2} h_i ds + \dot{j}_i, \]  

(17)

or:

\[ K^I \frac{\partial j^I_i}{\partial t} + K^\Phi \frac{\partial j^\Phi}{\partial \varphi} + \dot{j}_i, \]  

(18)

where both \( K^I \) and \( K^\Phi \) are of the order of the height and thickness of the ionosphere (\( r_2 - r_1 \)).

3. Simulation of thunderstorm regions

As mentioned above, it is still not possible – in the framework of the approach used here – to simulate the total effect of the thunderstorm currents on the ionospheric electric potential. First, this is because the global ionospheric potential distribution is computed to within an arbitrary constant (some specificities are discussed in the paper of Kartalev et al., in preparation). Thus, the expected increase of the ionospheric potential cannot

Fig. 4. The potential distribution obtained by AMIE techniques, applying simultaneous observations over both polar hemispheres (Lu et al., 1994).

Fig. 5. Distributions of the field-aligned currents, obtained for 27 January 1992, at 18:25 UT, applying the LiMIE data-based model (Papitashvili et al., 2001, 2002a; Papitashvili and Rich, 2002b). The relevant interplanetary magnetic field (IMF) components are: \( B_x = -17.2 \) nT, \( B_y = -9.1 \) nT. Solar parameters: F10.7 parameter: 230; sunspot number 180.
be examined directly. Here, we examine some indirect effects, focusing mainly on the ionospheric electric fields created by the presence of thunderstorms below.

We make use of a realistic case (27 January 1992, 18:25 UT), described in the paper of Lu et al. (1994), where electric potential distributions over both polar regions were obtained simultaneously by analyzing, via the AMIE$^1$ technique, the experimental data from satellites over both polar hemispheres (Fig. 4).

Then, we apply the LiMIE$^2$ data-based model (Papitashvili et al., 2001, 2002a; Papitashvili and Rich, 2002b) to obtain the distribution of the field-aligned currents for this specific time (Fig. 5). The solar parameters required are taken from www.dxlc.com/solar/history. The potential distributions over the polar regions, as a parts of the global potential distribution, derived from our model, are presented in Fig. 6.

The correct specification of the values of the input (to the ionosphere) due to thunderstorm currents remains quite a problem. There are two kinds of uncertainty:

- The detailed modelling of the equatorial tunnel is avoided in this approach by using the estimates described in Section 2.3.
- We do not have reliable numerical estimates for the real currents flowing up to the ionosphere above a thunderstorm region. The existing sophisticated satellite system for thunderstorm monitoring provides comprehensive information about the lightning intensity distribution globally, but there are no methods available yet for translating this information into the language of current densities. We therefore make use of information in the literature on atmospheric currents. Thus, Holzworth (1981) measured the upward current to be greater than $40 \times 10^{-6}$ A/km$^2$ using stratospheric balloon payloads. There are also estimates published by Makino and Ogawa (1984); see (Fig. 7).

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$^1$ Assimilative Mapping of Ionospheric Electrodynamics.

$^2$ Linear Modelling of Ionospheric Electrodynamics.
All the considerations and conclusions to be drawn have to be considered as being rather preliminary. The main thunderstorm sources are over the three active thunderstorm regions of America, Africa, and Asia/Oceania. We have modelled each thunderstorm centre as being active around 15 Local Time, with a maximum upward current of $70 \times 10^{-6}$ A/km$^2$.

We restrict the scope of our investigation here to finding answers to three important (in our opinion) questions, considering the thunderstorm current systems applied only below the equatorial ionosphere region:

- How do these thunderstorm currents affect the ionospheric electric fields within and near the equatorial tunnel?
- Are these effects different when the thunderstorm currents occur over the different continental regions (of America, Africa, and Asia/Oceania) at the appropriate UT?
- Is it possible to discover some specific features of the thunderstorm effect which might be experimentally detected – in order to provide some observational test of these model predictions?

3.1. Influence of thunderstorm currents on the electric potential near the magnetic dip equator

As already mentioned, the mathematical approach used here is not capable of demonstrating the possible
global increase of the ionospheric electric potential level due to thunderstorm currents flowing up to the ionosphere. The statement of the global problem (without the usual boundary conditions for the governing equation) requires the postulation of the potential at one point, which is taken as being somewhere on the equator. This could be (provisionally) called a “potential level condition”.

We demonstrate in Figs. 8 and 9 the results of numerical experiments without any thunderstorm input for 27 January 1992, at 18:25 UT, and then with an input for the case of American thunderstorm activity. The potential level condition mentioned is taken to be the same in both cases. Despite this latter condition, some increase of the ionospheric potential when thunderstorms are included in the model is evident. There are also some changes in the distribution of ionospheric potential at the equator, as well as at nearby low latitudes.

The departure of the potential from that at the dip equator increases with increasing latitude at all local times, with the greatest effect of the thunderstorms being from 19 to 24 Local Magnetic Time. We believe these are important results.

3.2. Thunderstorm influences on the Eastward and Southward near-equatorial electric fields

Much more substantial are the influences of the thunderstorm currents on the Eastward ionospheric electric
currents flowing in the equatorial ionosphere and at low latitudes (Figs. 10 and 11). The numerical results in Fig. 10 show that the thunderstorm electric currents change the order of magnitude of the Eastward electric fields at low and middle latitudes from microVolts/m to a fraction of 1 mV/m. There are changes in the temporal distribution patterns near the thunderstorm region, especially from 19 to 24 Local Magnetic Time. It is noteworthy that these values obtained are comparable with those expressing the contribution of the dynamo winds to the Eastward electric field distribution at low latitudes.

There is quite a different picture when the distribution of the Southward electric fields is considered (Figs. 12 and 13). The Southward (or Northward) field is always less than 2 mV/m, and it is clear that the occurrence of thunderstorms has essentially no effect on this. It seems that this effect is caused by the total problem geometry: The potential gradient ($E$ field direction) is along the normal to the magnetic field lines, which, as is seen from (5), is almost vertical there, because this normal is the unit vector $e_t$ along the $t$-direction. This prediction could probably be used when searching for experimental evidence for the effects of thunderstorms on the ionosphere.

Fig. 12. Distribution of the Southward electric field along the near-equator (magnetic) parallels: from the equator (solid line), to 30° latitude with 6° latitudinal distance between the lines. Top, without thunderstorm currents; bottom, with thunderstorm currents – the case for America.

Fig. 13. Distribution of the Southward electric field near the magnetic dip equator: top, without thunderstorm currents; bottom, with thunderstorm currents – the case for America (see the text).
3.3. Possible explanation of the UT dependence of the thunderstorm effect on near-equatorial electric fields

Another criterion for distinguishing, in observational data, the effects generated by atmospheric electricity from those due to dynamo action could be the local time and longitudinal dependence of these influences. Such a dependence could also be a key to understanding the mechanism which creates the Carnegie curve. Leaving a thorough investigation of this problem for future study, we provide here a comparison between Local Time distributions of the azimuthal electric field over the equator, which is the strongly affected parameter. In addition to the bottom of Fig. 11, presenting this distribution for the case of the Americas thunderstorm domain, we present in Fig. 14 the corresponding results for the Africa and Asia/Oceania thunderstorm domains.

The Eastward field at 20 Local Time is slightly larger for Asia/Oceania (0.19 mV/m) than for Africa (0.15 mV/m) and America (0.14 mV/m); see Fig. 11. From Fig. 13 it appears that thunderstorms double the existing Eastward electric field from 19 to 24 Local Time. The Local Magnetic Time (LMT) used here is the time measured (in magnetic coordinates) from the prime geomagnetic meridian; it is almost five hours (~4.7 h) after Universal Time. Thus, the maximum of thunderstorm activity which occurs near 15 Local Time (i.e., at 15 UT for Africa) corresponds to near 20 LMT. However, the overall situation is far from being simple, because some of the relevant processes are mainly organised by geomagnetic coordinates and others by geographic coordinates, which necessitates a further study of the detailed results obtained.

4. Summary

We have presented here a continuation of our efforts at making an indirect, yet quantitative, examination of the hypothesis of the contribution of upward thunderstorm currents to the formation and maintenance of the global atmospheric electric circuit. We have continued to apply the numerical model of the global ionospheric electrostatic potential which we developed earlier.

It has been shown here that the effects of the upward thunderstorm currents on the distribution of the ionospheric electric fields at low latitudes is very different for the Eastward and Southward components of the electric fields. The thunderstorm effect is quite considerable for the Eastward fields, whereas it is negligibly small for the Southward fields. These fields are directly connected to the experimentally well measured F-region vertical, zonal, and meridional plasma drifts (Fejer, 1997). Thus, it seems that there exists a challenging opportunity for performing an experimental check of the model predictions for the global influence of thunderstorms on the ionosphere.

The Local Time dependence of the thunderstorm effects found here could be a step towards understanding the role of the global distribution of areas of thunderstorm activity on the Carnegie curve phenomenon.

It is established by experiments and confirmed by models (e.g., Richmond et al., 2003) that at least three influences on equatorial electric fields can be of comparable importance: (1) global winds driven by polar heating; (2) direct penetration of polar cap electric fields to the equator that are partially shielded by the effects of Region-2 field-aligned currents; and (3) disturbance
winds driven by high-latitude heating and ion-drag acceleration. The present study demonstrates that the contribution of the thunderstorm generated currents may also be of essential importance on equatorial electric fields. Further model investigations are needed, especially those which provide ideas for quantitative comparisons with experiments.

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