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Transmission of electric fields due to distributed cloud charges in the atmosphere-ionosphere system

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Abstract

The transmission of electric fields in the lower atmosphere by thunder clouds with a suitable charge distribution profile has been modeled. The electromagnetic responses of the atmosphere are presented through Maxwell's equations together with a time-varying source charge distribution. The conductivities are taken to be exponentially graded function of altitude. The radial and vertical electric field components are derived for isotropic, anisotropic and thundercloud regions. The analytical solutions for the total Maxwell's current which flows from the cloud into the ionosphere under DC and quasi-static conditions are obtained for isotropic region. We found that the effect of charge distribution in thunderclouds produced by lightning discharges diminishes rapidly with increasing altitudes. Also, it is found that time to reach Maxwell's currents a maximum is higher for higher altitudes.

Keywords: Charged cloud; Time-varying source charge distribution; Electric potential and field; Lower ionosphere

1. Introduction

Electrified clouds and lightning play important role in the global electric circuit. The vertical component of the electric field relates to the global electric circuit while the horizontal component concerns the electrical coupling between the lower atmosphere and the ionized Earth's environment. A recent actively discussed problem is concerned with the electric currents and fields generated in the atmosphere above a thundercloud. Vertical coupling between troposphere and lower ionosphere by electric currents and fields for different situations has been addressed (Singh et al., 2004; De et al., 2009; Tonev and Velinov, 2016a, 2016b; Tonev, 2017). The parameters affect different scales in global electrical circuit: the electric currents contribute to the ionospheric potential, and at local scale the electric fields can cause electron heating and other effects in mesosphere and lower ionosphere. Cosmic ray variation effects on the parameters of the global atmospheric electric circuit have also been reported (Mateev and Velinov, 1992).

The distributions of electric charge in the electrified clouds introduce important effects in the ionosphere and into the region between the ionosphere and the Earth (Wilson, 1925; Hegai and Kim, 1990; MacGorman and Rust, 1998; Rakov and Uman, 2003). The electrical properties of the medium are changed greatly between thundercloud altitudes and the magnetosphere (Nickolaenko and Hayakawa, 1995; Greifinger and Greifinger, 1976). Various models are there to examine the electrical coupling between the Earth's upper and lower atmosphere (Velinov and Tonev, 1995a; Taranenko et al., 1993). The main sources of electric current in these regions are the thunderstorms which are randomly distributed in geographic areas (De et al., 2008; Velinov and Tonev, 1995a; Zhaofeng et al.,

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1998). During lightning discharges thundercloud charge changes rapidly and there are few modeling studies of quasi-static electric fields during such conditions (Pasko et al., 1995; Velinov and Tonev, 1995b; Rycroft and Cho, 1998; Tonev and Velinov, 2007). The electric currents above thundertsorm after a cloud-to-ground lightning discharge have also been proposed (Hale and Baginski, 1987; Velinov and Tonev, 2008; Mallios and Pasko, 2012; Janski and Pasko, 2014).

During sudden removal of thundercloud charge at low latitude due to lightning discharges, the quasi-electromagnetic fields are supposed to heat up the mesospheric electrons producing ionization and light (red sprite type of discharges). Strong lightning discharges associated with the sprites excite ULF transients and Schumann resonance bursts, which are impulsive events (Sorokin and Yaschenko, 1988; Fukunishi et al., 1997; Shalimov and Bösinger, 2006).

DC electric fields and currents above electrified clouds are studied by taking conductivity for both isotropic and anisotropic region of ionosphere with vertical magnetic field lines (Park and Dejnakarintra, 1973; Denisenko et al., 2013). Holzworth et al. (1985) modeled the conductivity profiles in the middle atmosphere above a nighttime thunderstorm. There are also few model studies of DC electric currents and fields by non-vertical magnetic field orientation in general (Kabirzadeh et al., 2015) and specifically for equatorial latitudes (Tonev and Velinov, 2002, 2003, 2016a, 2016b).

The galactic cosmic rays determine and modulate the electrical conductivities in the lower ionosphere-atmosphere system. Thus, the modeling of the electric fields is substantial for the coupling between the atmosphere and the ionosphere, and for solar-terrestrial relationships. A model for the penetration of DC thundercloud electric field in these regions has been presented in this paper which deals with the electromagnetic responses of the atmosphere simulated through Maxwell's equations together with a time-varying source charge distribution (Inan, 1990; Jones, 1970) and few unaddressed expressions are derived for the following regions: (1) isotropic (2) anisotropic and (3) thundercloud region.

The modified ellipsoidal-Gaussian distribution of the charge in the electrified cloud is adopted in this work. The conductivity profile of the medium is taken to be isotropic below 70 km height and anisotropic above 70 km. The Earth's surface is considered to be perfectly conducting. A general form of equation representing the thundercloud electric field component is deduced. Such representation is more appropriate than the representations of a thundercloud by monopole, dipole and tripole models. In the upper atmosphere, the varying electric fields are obtained though, in this model, axial symmetry of thundercloud charge distribution is considered.

In this work, we obtain analytical solutions for the electric field and the total Maxwell's current that flow from the cloud into the ionosphere under DC and quasi-static conditions, taking into account the spatial distribution and temporal behavior of the cloud electric charge. In the study, arbitrary inclination of the geomagnetic field lines, which is the actual case at different latitudes, are considered. Most previous studies in this area were based on the assumption for vertical orientation of geomagnetic field lines.

2. Mathematical formulation and solutions

The transmission of electric field due to thunderclouds has been investigated through the following equations written in cylindrical coordinates (r, φ, z) where axis z is vertical and r is the radial distance from the cloud charge center:

$$\nabla^2\Phi = \frac{-\rho_T(r,z)}{\varepsilon_0} \text{ at } 0 \leqslant z \leqslant z_E \tag{1}$$

$$\nabla.\bar{j} = 0 \text{ at } 0 \leqslant z \leqslant z_L \tag{2}$$

$$\bar{j} = \sigma_0\bar{E} \text{ at } z_U < z < z_I \tag{3}$$

$$\bar{j} = (\sigma_0 - \sigma_1)(\bar{E}.\hat{e}_0)\hat{e}_o + \sigma_1\bar{E} - \sigma_2\bar{E} \times \hat{e}_0 + \bar{j}_s \text{ at } z_I \leqslant z \leqslant z_E \tag{4}$$

$$\bar{j}_s = \frac{Q(t)}{2\pi\ r}\delta(r)\xi(z - z_e)\hat{e}_s \tag{5}$$

Φ is the electric potential of the electric field of the electrified cloud; ρ_T, total charge which follows ellipsoidal Gaussian distribution given later; ε_0, the free space permittivity; $\vec{j}_s$, the source current density assumed to generate a charge center at the height z_C in the cloud; $\bar{E}$, electric field of the electrified cloud; $\sigma_0, \sigma_1, \sigma_2$, the longitudinal, Pedersen and Hall conductivities respectively; $\hat{e}_0$, the unit vector in the direction of the external magnetic field; $Q(t)$, the source function which gives the total current injected at time t; ξ and δ, the unit Heaviside and Dirac function (Tonev and Velinov, 1996); $\hat{e}_s$, the vertical unit vector; $z = 0$, chosen to be the surface level; z, the axis of symmetry of the charge density distribution; z_E, the height between 100 km and 120 km; z_L and z_U are the lower and upper boundaries of the electrified cloud. The electric conductivity is isotropic in the atmospheric region (0, z_I), $z_I = 70$ km and anisotropic above $z = z_I$. Schematic heights above the surface of the Earth are given in Fig. 1. Electrical conductivity, neutral temperature and electron number density profiles of the Earth's atmospheric regions pertinent to this problem is given in Fig. 2 (Singh et al., 2004).

The radial and vertical electric field components are

$$E_r = -\frac{\partial\Phi}{\partial r} \text{ and } E_z = -\frac{\partial\Phi}{\partial z}. \tag{6}$$

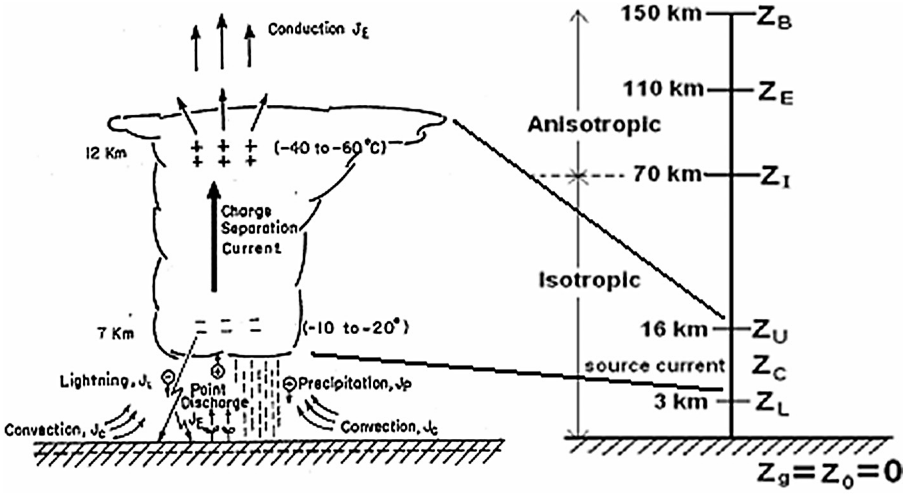

Fig. 1. Different current parameters involved within the distribution in cloud charge along with the schematic locations of various zones of the upper atmospheric region above the surface of the Earth. Discontinuity of longitudinal conductivity occurs at $z = z_L$ and $z = z_U$.

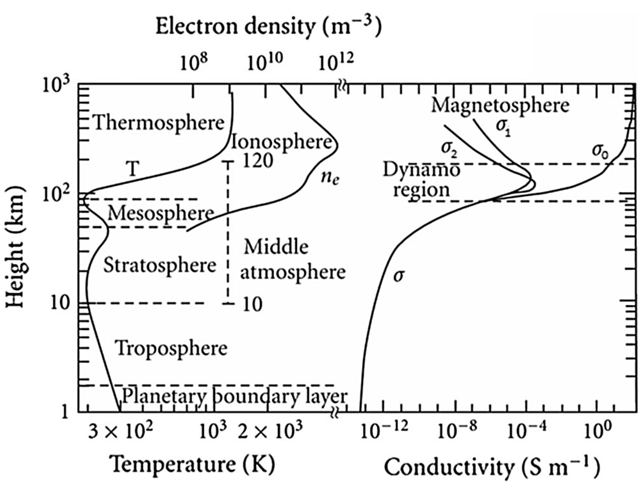

Fig. 2. Atmospheric electric conductivity, temperature and electron number density profile (Singh et al., 2004).

2.1. Isotropic region ($0 < z < z_L$, and $z_U < z < z_I$)

In this region, Eq. (2) yields,

$$\nabla(\sigma_1).\nabla(\sigma_2) + \sigma_1\nabla^2\Phi + \nabla(\sigma_2)\cdot(\nabla\Phi \times \hat{e}_0) + \sigma_2\nabla.(\nabla\Phi \times \hat{e}_0) + \nabla.j_s = 0 \tag{7}$$

Now, $\hat{e}_0 = \alpha(r,z)\hat{e}_r + \beta(r,z)\hat{e}_z$ and let $\nabla.\bar{j}_s = f(z)$, α and β are the representing terms for vertical dispersions of the charge density.

$$\therefore \nabla\Phi = \frac{\partial\Phi}{\partial r}\hat{e}_r + \frac{\partial\Phi}{\partial z}\hat{e}_z$$

$$\nabla.\hat{e}_0 = \frac{1}{r}\left[\frac{\partial}{\partial r}(r\alpha) + \frac{\partial}{\partial z}(r\beta)\right]$$

$$\nabla(\sigma_1) = \frac{\partial\sigma_1}{\partial z}\hat{e}_z, \nabla(\sigma_2) = \frac{\partial\sigma_2}{\partial z}\hat{e}_z$$

Thus, Eq. (7) takes the form,

$$\frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r^2}\frac{\partial\Phi}{\partial r} + \frac{\partial^2\Phi}{\partial z^2} + \frac{1}{h}\frac{\partial\Phi}{\partial z} + f(z,r) = 0 \tag{8}$$

$$\begin{aligned}&[\sigma_1 + \alpha^2(\sigma_0 - \sigma_1)]\frac{\partial^2\Phi}{\partial r^2} + 2\alpha\beta(\sigma_0 - \sigma_1)\frac{\partial^2\Phi}{\partial r\partial z} \\ &+ [\sigma_1 + \beta^2(\sigma_0 - \sigma_1)]\frac{\partial^2\Phi}{\partial z^2} + \left[\frac{\sigma_1}{r} + \alpha\beta\frac{\partial}{\partial z}(\sigma_0 - \sigma_1)\right] \\ &+ (\sigma_0 - \sigma_1)\left[\frac{\alpha^2}{r} + 2\alpha\frac{\partial\alpha}{\partial r} + \beta\frac{\partial\alpha}{\partial z} + \alpha\frac{\partial\beta}{\partial z}\right]\frac{\partial\Phi}{\partial r} \\ &+ \left[\frac{\partial\sigma_1}{\partial z} + \beta^2\frac{\partial}{\partial z}(\sigma_0 - \sigma_1) + (\sigma_0 - \sigma_1)\frac{\alpha\beta}{r} \right. \\ &\left. + 2\beta\frac{\partial\beta}{\partial z} + \alpha\frac{\partial\beta}{\partial r} + \beta\frac{\partial\alpha}{\partial r}\right]\frac{\partial\Phi}{\partial z} + f(r,z) = 0\end{aligned} \tag{9}$$

For isotropic region, $0 < z < z_L$, $\sigma_0 = \sigma_1 = C_1\exp(\frac{z}{h})$

Here, h is normalizing scaling height and C_1 is arbitrary constant.

Solution of this equation is obtained as

$$\Phi(r,z) = \int_0^\infty J_0(rk)[a_i(k)\exp(c_1 z) + b_i(k)\exp(c_2 z)]dk \tag{10}$$

Now, $i = 0$ for $0 \leqslant z \leqslant z_L$ and $i = 1$ for $z_U \leqslant z \leqslant z_I$

where $J_0(rk)$ is the Bessel function of zero-th order.

$$c_1, c_2 = -\frac{1}{2h_1} \pm \left[\sqrt{\frac{1}{(2h_1)^2} + k^2} + \frac{k}{k - \gamma v} + \frac{h_1}{h_1 - h_0}\right]$$

With h_0, h_1 the corresponding scale heights.

Hence, electric fields E_r and E_z have been derived from Eq. (10) as

$$E_r = -\frac{\partial\Phi}{\partial r} = \int_0^\infty kJ_1(rk)[a_i(k)\exp(c_1 z) + b_i(k)\exp(c_2 z)]dk \tag{11a}$$

$$E_z = -\frac{\partial\Phi}{\partial z} = \int_0^\infty J_0(rk)[c_1 a_i(k)\exp(c_1 z) + c_2 b_i(k)\exp(c_2 z)]dk \tag{11b}$$

where $J_1(rk)$ is the Bessel function of first order.

The variation of the field component values for different heights can be evaluated with these results. The upward Maxwell current can be calculated by using the transient electric field. In cylindrical coordinates, the Maxwell's current through the horizontal cross-section at altitude z is determined from:

$$(J)_{\text{Maxwell}} = 2\pi\int_0^\infty \left(\sigma E_z + \varepsilon\frac{\partial E_z}{\partial t}\right)dr \tag{12}$$

The vertical component E_z of the electric field is studied in this work as dependent on time.

2.2. Anisotropic region ($z_I \leqslant z \leqslant z_E$)

Above 70 km height, the conductivity is tensorial in nature (Fullekrug and Sukhorukov, 1999). For $110 < z_E < 125$ km, the longitudinal conductivity σ_0 becomes very large compared to transverse conductivities.

For the anisotropic region,

$$\sigma_0 = C_A\exp\left(\frac{z}{h_0}\right), \sigma_1 = C_A\exp\left(\frac{z}{h_1}\right)$$

where C_A is also arbitrary constant.

$$\frac{\partial\sigma_0}{\partial z} = \frac{\sigma_0}{z}, \frac{\sigma_0}{\sigma_1} = \exp\left(\frac{z}{h_0} - \frac{z}{h_l}\right) = \exp\left(\frac{z}{l}\right)$$

$$\frac{\partial\sigma}{\partial z} = \frac{\sigma_1}{z_1}, \frac{1}{l} = \frac{1}{h_0} - \frac{1}{h_l}$$

where h_0, h_1 and h_l are the corresponding scale heights.

When Earth's magnetic field be considered,

$$\alpha(r,z) = -\frac{r(a+z)}{[\{r^2 + (a+z)^2\}\{r^2 + 4(a+z)^2\}]^{\frac{1}{2}}}$$

$$\beta(r,z) = -\frac{r^2 + 2(a+z)^2}{[\{r^2 + (a+z)^2\}\{r^2 + 4(a+z)^2\}]^{\frac{1}{2}}}$$

where a is the radius of the Earth.

Since $(a+z) \gg r$, we use the approximation $\alpha(r,z) \equiv -\frac{r}{2(a+z)}$

$$\frac{\partial\alpha}{\partial r} = -\frac{1}{2(a+z)}, \frac{\partial\alpha}{\partial z} = \frac{r}{2(a+z)^2} \equiv 0$$

$$\beta(r,z) \equiv -1$$

Thus, $\frac{\partial\beta}{\partial r} = \frac{\partial\beta}{\partial z} = 0$, $\alpha^2 = 0$, $\beta^2 = 1$

Also Eq. (8) thus yields

$$\frac{\partial^2\Phi}{\partial r^2} - \frac{r}{a}\left[1 - \exp\left(\frac{z}{l}\right)\right]\frac{\partial^2\Phi}{\partial r\partial z} + \exp\left(\frac{z}{l}\right)\frac{\partial^2\Phi}{\partial z^2} + \left[\frac{1}{r} - \frac{r}{2a}\left\{\frac{1}{h_1} - \frac{1}{h_0}\exp\left(\frac{z}{l}\right)\right\}\right]\frac{\partial^2\Phi}{\partial z^2} + \left[\frac{1}{r} - \frac{r}{2a}\left\{\frac{1}{h_1} - \frac{1}{h_0}\exp\left(\frac{z}{l}\right)\right\}\right]\frac{\partial\Phi}{\partial r} + \left[\left(\frac{1}{h_0} + \frac{r}{a}\right)\exp\left(\frac{z}{l}\right) - \frac{r}{a}\right]\frac{\partial\Phi}{\partial z} + g(r,z) = 0 \tag{13}$$

the solution has been obtained as

$$\Phi(r,z) = [f(z)]^n\int_0^\infty \left[J_0(rk)\{A(k)I_n[kf(z)] + B(k)K_m[kf(z)]\} + \left[\left(r^2 + \frac{k^2}{r_k^2}\right)J_0\{kf(z)\} - k^2\right]\right]dk \tag{14}$$

$$n = \frac{h_1}{h_p - h_0}, f(z) = g\exp\left(-\frac{z - z_I}{g}\right)r_k, g = \frac{2h_1h_0}{h_1 - h_0} + \frac{h_1^2}{h_0}$$

where $A(k)$, $B(k)$ are the corresponding coefficients of I_n and K_m respectively with r_k, h_p and g are the necessary substituitions.

Hence, electric fields E_r and E_z have been derived as

$$E_r = -\frac{\partial\Phi}{\partial r} = [f(z)]^n\int_0^\infty kJ_1(rk)\{A(k)I_n[kf(z)] + B(k)K_n[kf(z)]\}dk \tag{15a}$$

$$E_z = -\frac{\partial\Phi}{\partial z} = n(z - z_I)\exp\left(-\frac{z - z_1}{g}\right)[f(z)]^{n-1}\int_0^\infty J_0(rk) \times \{A(k)I_n[kf(z)] + B(k)K_n[kf(z)]\}dk + [f(z)]^n\int_0^\infty J_0(rk)\{A(k)kf'(z)I_{n-1}[kf(z)] + B(k)kf'K_{n-1}[kf(z)]\}dk \tag{15b}$$

2.3. Thundercloud region ($z_L \leqslant z \leqslant z_U$)

The charge is assumed to have an ellipsoidal Gaussian distribution given by Eq. (5).

Hence, $\rho_T = \rho_{\text{model}} + \rho_S$ (16)

Where $\rho_{\text{model}} = \gamma\exp\left[\frac{r^2}{\alpha^2} - \frac{(z - z_0)}{\beta^2}\right], z_L \leqslant z \leqslant z_U$ (16a)

and $\rho_S = \frac{Q(t)}{2\pi\ r}\delta(r)\xi(z - z_0), 0 \leqslant z \leqslant z_U,$
$z_0 = (z_L + z_U)/2.$ (16b)

γ is the normalization constant. The charge is higher for small α^2 and β^2. The maximum density is reached at $r = 0, z = z_0$.

For the thundercloud region, $z_L \leqslant z \leqslant z_U$

$$\Phi_n(r,z) = \int_0^\infty J_0(kr)[C(k)\exp(-kz) + D(k)\exp(+kz) + \upsilon(z,k)]dk \quad (17)$$

where $C(k) = a(k)\ \ b(k)$, $D(k) = a(k)\ c\ (k)$ and $\upsilon(z,k)$ is function of z and k.

Hence electric fields around the electrified cloud, $z_L \leqslant z \leqslant z_U$

$$E_r = -\frac{\partial\Phi}{\partial r} = \int_0^\infty kJ_1(rk)[C(k)\exp(-kz) + D(k)\exp(+kz) + \upsilon(z,k)]dk \quad (18a)$$

$$E_z = -\frac{\partial\Phi}{\partial z} = \int_0^\infty J_0(rk)[kC(k)\exp(-kz) + kD(k)\exp(+kz) - \upsilon'(z,k)]dk \quad (18b)$$

where $J_1(rk)$ is the Bessel function of first order and $\upsilon'(z,k)$ is the first order differentiation of $\upsilon(z,k)$ with respect to z.

3. Results and discussions

Committee on Space Research International Reference Atmosphere (CIRA) data are used in the computation. For our geographical position Kolkata (22.56° N, 88.5°E) and at the isotropic region of the atmosphere, the values of the electron densities, neutral particles, and ion and electron temperatures are taken from this model. Different conductivity parameters are taken from the conductivity profile shown in Fig. 2 (Singh et al., 2004). MATLAB programs are used to calculate the values of vertical electric fields (E_z) and $(J)_{\text{Maxwell}}$ within the medium for some specific altitudes given below. The output of our program is plotted through Origin 5.0.

Total Maxwell's current $(J)_{\text{Maxwell}}$ as a function of time above a thundercloud is depicted in Fig. 3, different heights as parameters within the isotropic region. Five different altitudes at 17, 20, 30, 40 and 60 km above the upper boundary of the electrified cloud are chosen for computation of $(J)_{\text{Maxwell}}$ to understand how the magnitude of current varies with altitudes. The results relate to a time period after having a lightning discharge. At 17 km height, total Maxwell current reaches its maximum 44 A within a very short time of 0.002 s, i.e., 2 ms from the initiation of a lightning discharge while at 60 km height, it takes 7 ms to reach 15 A of current. Thus, it has been found that time to reach currents a maximum is higher for higher altitudes though the response is very fast.

Variations of vertical electric fields (E_z) due to cloud charge distribution at Kolkata are shown in Fig. 4. Source heights are chosen at 4 km (near lower boundary of electrified cloud charge) and another at 10 km (near upper boundary of electrified cloud charge). Fields (Eq. (11b)) are computed in isotropic region. Maximum values of electric fields obtained are 48 and 66 Vm^{-1} when source are at 4 km height and field points of computation/observations 15 and 20 km, respectively. When field points are chosen at 30 and 60 km heights for source at 10 km, then those values are obtained as 24 and 0.65 Vm^{-1} respectively. Thus, effect of charge distributions due to lightning diminishes rapidly while altitude increases.

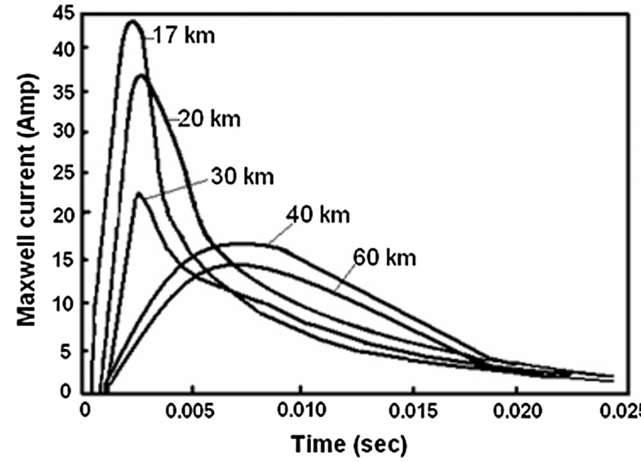

Fig. 3. Variation of Maxwell current $(J)_{\text{Maxwell}}$ at different altitudes within the isotropic region. Time to reach currents a maximum is higher for higher altitudes which are marked in the plot. Five different altitudes above the upper boundary of the electrified cloud are chosen for computation.

4. Conclusion

Introducing a time-varying realizable charge distribution in the form of modified ellipsoidal-Gaussian conductivity profile, a model for the electric field components around a charged cloud have been considered in this work. The equations for electric potential and field components at different heights of the atmosphere are derived. Also, analytical solutions of the total Maxwell's current under DC and quasi-static conditions have been worked out. Data from CIRA and other published work are used in computation technique through MATLAB and outcome have been presented through Origin. Total Maxwell current is found to be time dependent and the response is very fast within the isotropic region of the atmosphere. Variations have been found within 2 to 7 ms up to 70 km altitude. On the otherhand, solutions for vertical electric fields are determined for sources located at two different heights, one near lower boundary of electrified cloud charge (4 km) and other near upper boundary of electrified cloud charge (10 km) and we found that magnitude of fields reduces rapidly with increasing altitudes.

Thus, it can be concluded that thunderclouds are the important sources of localized electric fields in the lower atmosphere. These electric fields can initiate field-aligned electron density irregularities in the ionosphere which is

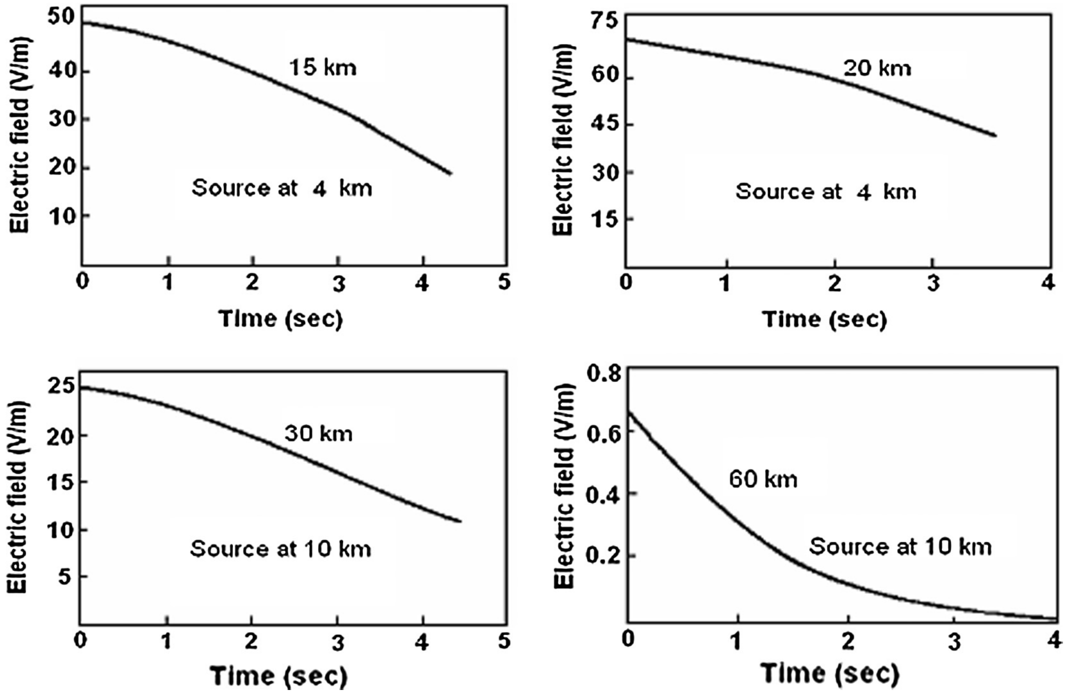

Fig. 4. Variations of electric fields at Kolkata (22.56°N, 88.5°E) Source heights are chosen at 4 km (near lower boundary of electrified cloud charge) and another at 10 km (near upper boundary of electrified cloud charge). Fields are computed in isotropic region. Maximum values are 48, 66, 24 and 0.65 V/m respectively.

dependent on the charge distribution. Coupling between the troposphere and the ionosphere is critically dependent on the height variations of electrical conductivity. Rigorous studies regarding this coupling between isotropic and anisotrpic regions will be contemplated in next work.

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References

De, S.S., Adhikari, S.K., De, M., Bandyopadhyay, B., Guha, A., Paul, S., De, B.K., 2008. A study on heating of the lower ionosphere during lightning. Indian J. Radio Space Phys. 37, 109–113.

De, S.S., De, B.K., Bandyopadhyay, B., Paul, S., Sanfui, M., Haldar, D. K., Bose, M., Chattopadhyay, G., 2009. Studies on non-linear Travelling Ionospheric Disturbances and mode coupling within the auroral region. In: Computers and Devices for communication, CODEC – 2009, IEEE, pp. 1–4.

Denisenko, V.V., Ampferer, M., Pomozov, E.V., Kitaev, A.V., Hausleitner, W., Stangl, G., Biernat, H.K., 2013. On electric field penetration from ground into the ionosphere. J. Atmos. Sol. Terr. Phys. 102, 341–353.

Fullekrug, M., Sukhorukov, A.I., 1999. The contribution of anisotropic conductivity in the ionosphere to lightning flash bearing deviations in the ELF/ULF range. Geophys. Res. Lett. 26, 1109–1112. http://dx.doi.org/10.1029/1999GL900174.

Fukunishi, H., Takahashi, Y., Sato, M., Shono, A., Fujito, M., Watanabe, Y., 1997. Ground-based observations of ULF transients excited by strong lightning discharges producing elves and sprites. Geophys. Res. Lett. 24, 2973–2976.

Greifinger, C., Greifinger, P., 1976. Transient ULF electric and magnetic fields following a lightning discharge. J. Geophys. Res. 81, 2237–2247. http://dx.doi.org/10.1029/JA081i013p02237.

Hale, L.C., Baginski, M.E., 1987. Current to the ionosphere following a lightning stroke. Nature 329, 814–816. http://dx.doi.org/10.1038/329814a0.

Hegai, V.V., Kim, V.P., 1990. The formation of a cavity in the night-time midlatitude ionospheric E-region above a thundercloud. Planet. Space Sci. 38, 703–707.

Holzworth, R.H., Kelley, M.C., Siefring, C.L., Hale, L.C., Mitchell, J.D., 1985. Electrical measurements in the atmosphere and the ionosphere over an active thunderstorm: 2. Direct current electric fields and conductivity. J. Geophys. Res. 90, 9824–9830.

Inan, U.S., 1990. VLF heating of the lower ionosphere. Geophys. Res. Lett. 17, 729–732.

Jansky, J., Pasko, V.P., 2014. Charge balance and ionospheric potential dynamics in time-dependent global electric circuit model. J. Geophys. Res. 119, 1–20. http://dx.doi.org/10.1002/2014JA020326.

Jones, D.L., 1970. Electromagnetic radiation from multiple return strokes of lightning. J. Atmos. Terr. Phys. 32, 1077–1093. http://dx.doi.org/10.1016/0021-9169(70)90119-4.

Kabirzadeh, R., Lehtinen, N.G., Inan, U.S., 2015. Latitudinal dependence of static mesospheric E fields above thunderstorms. Geophys. Res. Lett. 42, 4208–4215. http://dx.doi.org/10.1002/2015GL064042.

MacGorman, D.R., Rust, W.D., 1998. Electrical Structure of Thunderstorms. Oxford University Press, Oxford, p. 432.

Mallios, S.A., Pasko, V.P., 2012. Charge transfer to the ionosphere and to the ground during thunderstorms. J. Geophys. Res. 117, A08303.

Mateev, L., Velinov, P.I.Y., 1992. Cosmic ray variation effects on the parameters of the global atmospheric electric circuit. Adv. Space Res. 12, 353–356.

Nickolaenko, A.P., Hayakawa, M., 1995. Heating of the lower ionosphere electrons by electromagnetic radiation of lightning discharges. Geophys. Res. Lett. 22, 3015–3018. http://dx.doi.org/10.1029/95GL01982.

Park, C.G., Dejnakarintra, M., 1973. Penetration of thundercloud electric fields into the ionosphere and magnetosphere, 1. Middle and auroral latitudes. J. Geophys. Res. 84, 960–964.

Pasko, V.P., Inan, U.S., Taranenko, Y.N., Bell, T.F., 1995. Heating, ionization and upward discharges in the mesosphere due to intense quasi- electrostatic thundercloud fields. Geophys. Res. Lett. 22, 365–368.

Rakov, V.A., Uman, M.A., 2003. Lightning: Physics and Effects. Cambridge University Press, Cambridge.

Rycroft, M.J., Cho, M., 1998. Modelling electric and magnetic fields due to thunderclouds and lightning from cloud-tops to the ionosphere. J. Atmos. Sol-Terr. Phys. 60, 889–893. http://dx.doi.org/10.1016/S1364-6826(98)00037-6.

Shalimov, S.L., Bösinger, T., 2006. An alternative explanation for the ultra-slow tail of sprite-associated lightning discharges. J. Atmos. Sol.-Terr. Phys. 68, 814–820. http://dx.doi.org/10.1016/j.jastp.2005.12.001.

Singh, D.K., Singh, R.P., Kamra, A.K., 2004. The electrical environment of the Earth's atmosphere: a review. Space Sci. Rev. 113, 375–408. http://dx.doi.org/10.1023/B:SPAC.0000046747.32359.d8.

Sorokin, V.M., Yaschenko, A.K., 1988. Propagation of Pi2 pulsations in the lower ionosphere. Geomag. Aeronomy 28, 655–660.

Taranenko, Y.N., Inan, U.S., Bell, T.F., 1993. Interaction with the lower ionosphere of electromagnetic pulses from lightning: heating, attachment, and ionization. Geophys. Res. Lett. 20, 2675–2678.

Tonev, P., 2017. Influence of solar activity on dimensions of red sprites caused by long-term variations of strato-mesospheric conductivity – model Study. C. R. Acad. Bulg. Sci. 70, 111–120.

Tonev, P., Velinov, P.I.Y., 2016a. Influence of solar activity on red sprites and on vertical coupling in the system stratosphere-mesosphere. J. Atmos. Sol. Terr. Phys. 141, 27–38. http://dx.doi.org/10.1016/j.jastp.2015.11.018.

Tonev, P., Velinov, P.I.Y., 2016b. Vertical coupling between troposphere and lower ionosphere by electric currents and fields at equatorial latitudes. J. Atmos. Sol.-Terr. Phys. 141, 39–47. http://dx.doi.org/10.1016/j.jastp.2015.10.012.

Tonev, P.T., Velinov, P.I.Y., 2007. Electric atmosphere-ionosphere vertical coupling above thunderstorms of different intensity. J. Atmos. Sol.-Terr. Phys. 69, 2510–2522.

Tonev, P., Velinov, P.I.Y., 2003. Quasi-electrostatic fields in the near-earth space produced by lightning and generation of runaway electrons in ionosphere. J. Adv. Space Res. 31, 1443–1448.

Tonev, P., Velinov, P.I.Y., 2002. Electrostatic fields above thunderclouds at different latitudes and their ionospheric effects. J. Adv. Space Res. 30, 2625–2630.

Tonev, P.T., Velinov, P.I.Y., 1996. A quasi-DC model of electric fields in the ionosphere-ground region due to electrified clouds. J. Atmos. Terr. Phys. 58, 1117–1124. http://dx.doi.org/10.1016/0021-9169(95)00112-3.

Velinov, P.I.Y., Tonev, P.T., 1995a. Thundercloud electric field modelling for the ionosphere-Earth region 1. Dependence on cloud charge distribution. J. Geophys. Res. 100, 1477–1485. http://dx.doi.org/10.1029/94JD00286.

Velinov, P.I.Y., Tonev, P., 1995b. Modeling the penetration of thundercloud electric fields into the ionosphere. J. Atmos. Terr. Phys. 57, 687–694. http://dx.doi.org/10.1016/0021-9169(94)E0016-G.

Velinov, P.I.Y., Tonev, P.T., 2008. Electric currents from thunderstorms to the ionosphere during a solar cycle: quasi-static modeling of the coupling mechanism. Adv. Space Res. 42, 1569–1575.

Wilson, C.T.R., 1925. The electric field of a thundercloud and some of its effects. In: Proc. Roy. Soc., London, 37, 32D.

Zhaofeng, Ma., Croskey, C.L., Hale, L.C., 1998. The electrodynamic responses of the atmosphere and ionosphere to the lightning discharge. J. Atmos. Sol.-Terr. Phys. 60, 845–861. http://dx.doi.org/10.1016/S1364-6826(98)00020-0.