XV International Conference on Atmospheric Electricity, 15-20 June 2014, Norman, Oklahoma, U.S.A.

3D Modeling Electromagnetic Response of the Atmosphere to the Lightning Discharge

Stanislav S. Davydenko[1,*], Stepan A. Savikhin[2], Alexander S. Sergeev[1], Sergei A. Zolotov[2]

1. Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
2. Special Computing Technologies LCC, Nizhny Novgorod, Russia

ABSTRACT: A 3D numerical model of the electromagnetic field of an isolated lightning discharge in the plane atmosphere is developed. The discharge is presented as a spatially extended pulse current producing one or two extended charge regions of arbitrary shape inside the thundercloud in the case of cloud-to-ground (CG) or intra-cloud (IC) flash. A temporal profile of the discharge current depends on the flash type and generally may consist of different components, such as the return stroke and continuous current. Disturbance of the electric conductivity inside the thundercloud as compared to the surrounding air and anisotropy of the conductivity of the upper atmosphere are taken into account. The model describes both the quasistatic electric field (slow transient) caused by the Maxwell's relaxation of the charge disturbance and the electromagnetic pulse (fast transient) generated mainly by the return stroke. An influence of the basic parameters of the discharge on spatiotemporal distributions of the atmospheric electric field is examined. In particular, the effect of the disturbance of the electric conductivity inside the thundercloud and altitude(s) of the charge region(s) on the burst of the quasistatic electric field following the lightning discharge is considered. By way of example, the dynamics of the electric field and charge density in the vicinity of the thundercloud after an asymmetric intra-cloud discharge is presented. To illustrate the effect of the anisotropic conductivity of the upper atmosphere, a disturbance of the electric field at high altitudes over the thundercloud after the axially symmetric cloud-to-ground discharge is presented. An application of the model for solving both direct and inverse problems of the atmospheric electrodynamics is discussed.

INTRODUCTION

Lightning discharges play an important role in global and local atmospheric electric processes ranging from various types of the transient luminous events in the middle and upper atmosphere to the formation of AC and DC global electric circuits. This is why modeling the electric response of the conducting atmosphere to the lightning discharge is still a subject of intensive research. Depending on the subject of the research, the developed models are based on the curl-free (quasi-static) approximation for the electric field or on the complete set of Maxwell equations. The quasistatic axially symmetric models describing the extended burst of the electric field (slow transient) following the lightning discharge, in particular, are used to simulate the dynamics of sprite halos and sprite streamers (see, for instance, [Qin et al., 2013]) and

---

[*] Institute of Applied Physics RAS, 46 Ulyanova str., 603950 Nizhny Novgorod, Russia; *e-mail:* davyd@appl.sci-nnov.ru

to estimate the lightning discharge contribution to the global circuit [Mareev et al., 2008]. The models based on the complete set of Maxwell's equations are able to describe also the lightning-induced electromagnetic pulse, so these are usually used for simulation of the upper atmosphere heating/ionization after the lightning discharge and optical emissions known as elves (see, for instance, [Marshall, 2012]). Being focused mainly on the upper atmosphere response to the electromagnetic pulse, these models usually consider a short time interval after the lightning discharge. However, it seems important to consider the lightning-induced atmospheric electric field at larger times to estimate an influence of the upper atmosphere on the charge transfer and current system arising after the lightning discharge. Some evidences that this influence may be significant were presented by Ma et al. [1998].

To consider the above problem, we developed a 3D numerical model of the electric environment of an isolated lightning discharge based on a complete set of the Maxwell's equations. The model describes both the electromagnetic pulse generated mainly by the return stroke and slow transient electric field driven by the Maxwell relaxation of the lightning-produced disturbance of the charge density. Further, we briefly describe the main points of the model, present sample calculation results for lower and upper atmosphere, and discuss possible applications of the developed model.

MODEL BASICS

The electric $(\mathbf{E})$ and magnetic $(\mathbf{H})$ fields in the vicinity of the lightning discharge in the plain atmosphere are determined by the Maxwell equations:

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}, \quad \nabla \times \mathbf{H} = \boldsymbol{\sigma}\mathbf{E} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mathbf{j}_{\mathrm{ext}}(\mathbf{r},t), \quad \nabla \cdot \mathbf{E} = \rho / \varepsilon_0, \quad \nabla \cdot \mathbf{H} = 0. \tag{1}$$

Here $\mathbf{j}_{\mathrm{ext}}(\mathbf{r},t)$ is the discharge (source) current density, tensor $\boldsymbol{\sigma}(\mathbf{r})$ describes the electric conductivity of the medium, ρ is the electric charge density, ε_0 and μ_0 are the electric and magnetic constants, respectively. Generally, distributions of both the discharge current density and electric conductivity are assumed to be arbitrary. Since the Cartesian coordinate system is adopted in the model, the computational domain has the shape of a parallelepiped with a height of (up to) 150 km and horizontal sizes of a few hundreds kilometers. The top and bottom plane boundaries of the domain are assumed to be perfect conductors. The equations (1) were solved numerically using the FDTD method.

The atmospheric conductivity is assumed to be isotropic up to the height of 70 km and anisotropic at higher altitudes. In particular, in the lower atmosphere away from the source region the conductivity grows exponentially with the height z according to the relation $\sigma_0 \exp(z/H)$, where $\sigma_0 = 5 \cdot 10^{-14}$ S/m is the conductivity near the ground (at the height $z = 0$) and $H = 6 \cdot 10^3$ m is the scale height of the conductivity profile. Near the source, inside the thundercloud of arbitrary shape, the conductivity is assumed to be disturbed: the ratio of the conductivities inside and outside the thundercloud at the same altitude is one of the parameters of the model.

The model discharge current is localized inside the thundercloud and generally may have an arbitrary direction and spatial distribution. Depending on the discharge type (intracloud or cloud-to-ground) the source current may include different constituents, such as the return stroke, continuous current, and M-component, with the appropriate temporal profiles (see [Davydenko et al., 2011]). As a result, in the case of intracloud discharge the source current produces two charged regions of opposite polarity and arbitrary shape inside the thundercloud, or one charged region in the case of cloud-to-ground discharge.

SAMPLE ELECTRIC ENVIRONMENTS OF DIFFERENT SOURCES

To illustrate the capabilities of the model, further we consider the electric environments of two different current sources. The first one is assumed to be asymmetric, and in this case we shall focus mainly on the electric field and charge density dynamics inside and in the vicinity of the thundercloud. The second source is assumed to be axially symmetric, and in this case we shall be interested in the electric field at high altitudes over the source region.

Electric environment of the asymmetric source

As the simplest example of the asymmetric source, we considered the intracloud discharge with the discharge current inclined to the vertical axis. In this case, the generated charged regions of opposite polarities are located at the heights about 4.5 and 9.5 km, respectively, and displaced horizontally (see Fig.1). For convenience, we assumed that the total neutralized charge in each of the regions is equal to 1 C. The discharge took place inside the thundercloud of radius 10 km, the top and bottom boundaries of the thundercloud are located at the heights about 0.7 and 10.5 km, respectively; the conductivity inside the thundercloud is about 10 times less as compared to the conductivity of the fair-weather atmosphere at the same altitude.

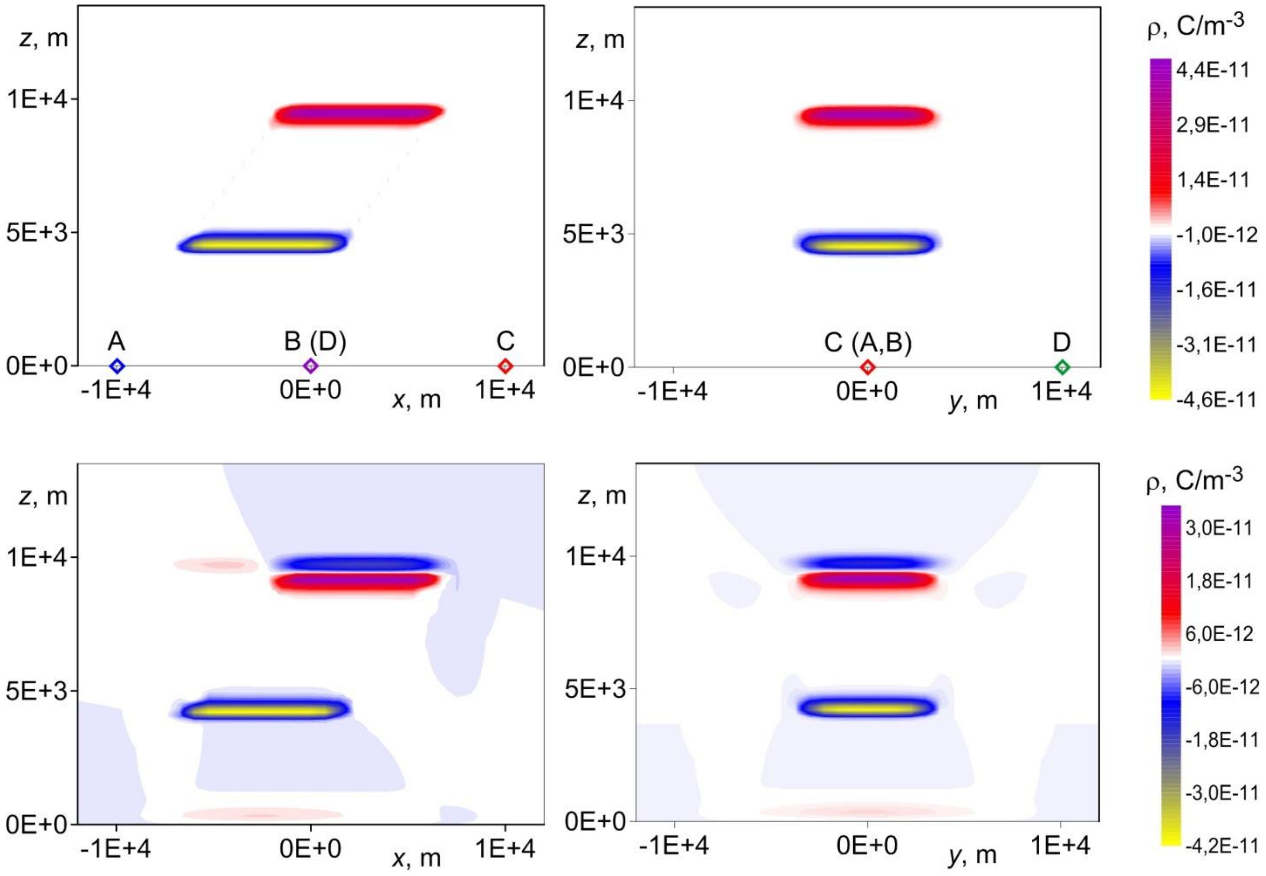

Fig.1. Distributions of the electric charge density over the vertical cross sections of the calculation domain just after the intracloud discharge (top panels) and 60 s later (bottom panels). The screening charge layer at the bottom panel is well recognized, especially near the top boundary of the thundercloud.

Distributions of the charge density just after the discharge and 60 s later are shown in Fig.1. One can see a diminution of the initial charge density with time and appearance of the inhomogeneous screening charge layer near the boundary of the thundercloud. Such 3D calculations of the charge transfer after the lightning flash of arbitrary spatial structure may be helpful, in particular, for more detailed description of the formation and properties of the screening charge layer near the boundary of the thundercloud. Also, based on the above calculations, one can obtain more reliable estimates of the contribution of the lightning discharge to the global circuit. It should be noted that the model can be used to retrieve the basic spatiotemporal parameters of the discharge. One of the simplest ways to solve the inverse problem is to match the model and measured profiles of the electric field in different points in the vicinity of the discharge (see Fig.2). Of course, this procedure requires an adequate parameterisation of the electric structure of the discharge and is more effective if based also on the additional information about the discharge (the radar or/and balloon soundings, LMA data etc.).

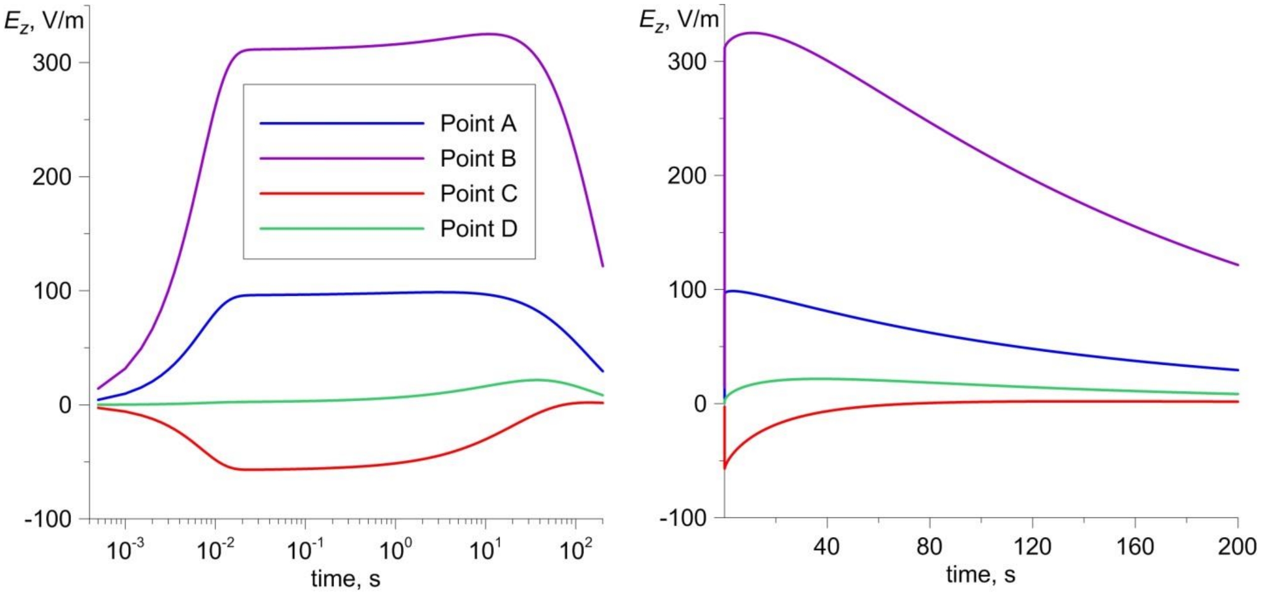

Fig.2. Temporal profiles of the vertical electric field in different points near the asymmetric lightning discharge. The points A, B, C, and D are indicated in Fig.1. It should be noted that generally the maximum of the electric field does not correspond to the duration of the discharge (here the decay time of the discharge current is 10 ms).

Electric field in the upper atmosphere over the symmetric source

As another sample, let us consider the electric field of the symmetric source in anisotropic upper part of the atmosphere. Here, the source represents the cloud-to-ground discharge with the height and radius of the arisen charged region of about 9.5 and 4 km, respectively. According to the previous case, the total neutralized electric charge is assumed to be equal to 1 C. In contrast to the previous consideration, in the upper atmosphere the decay time of the electric field in the order of magnitude is equal to the duration of the discharge, so the temporal profile of the discharge current becomes an important factor determining the dynamics of the electric field. Here we assumed that the discharge current reaches the maximum value within 40 μs and total duration of the discharge is equal to 1 ms. Another important factor, exerting an influence on the electric field, is the conductivity distribution. The conductivity in the lower atmosphere is assumed to be the same as in the above section. At heights of more than about 70 km the conductivity is anisotropic, so the parallel, Hall and Pedersen components of the conductivity tensor are taken into account; here, the geomagnetic field is assumed to be inclined at 40 degrees to the vertical axis.

In Fig.4, the vertical cross-sections of the electric field distributions at the time moment 0.3 ms after the cloud-to-ground discharge are presented. The cross-section plane contains both the vertical axis and the magnetic field vector. It should be noted that with time the electric field component directed along the magnetic field becomes substantially less as compared to the transversal component. Also, an asymmetry of the total electric field distribution and formation of the ELF pulse are well recognized. Temporal profiles of the electric field components in different points at the height 75 km are shown in Fig.4. As seen, the profiles depend both on the distance to the discharge axis and azimuth of the observation point.

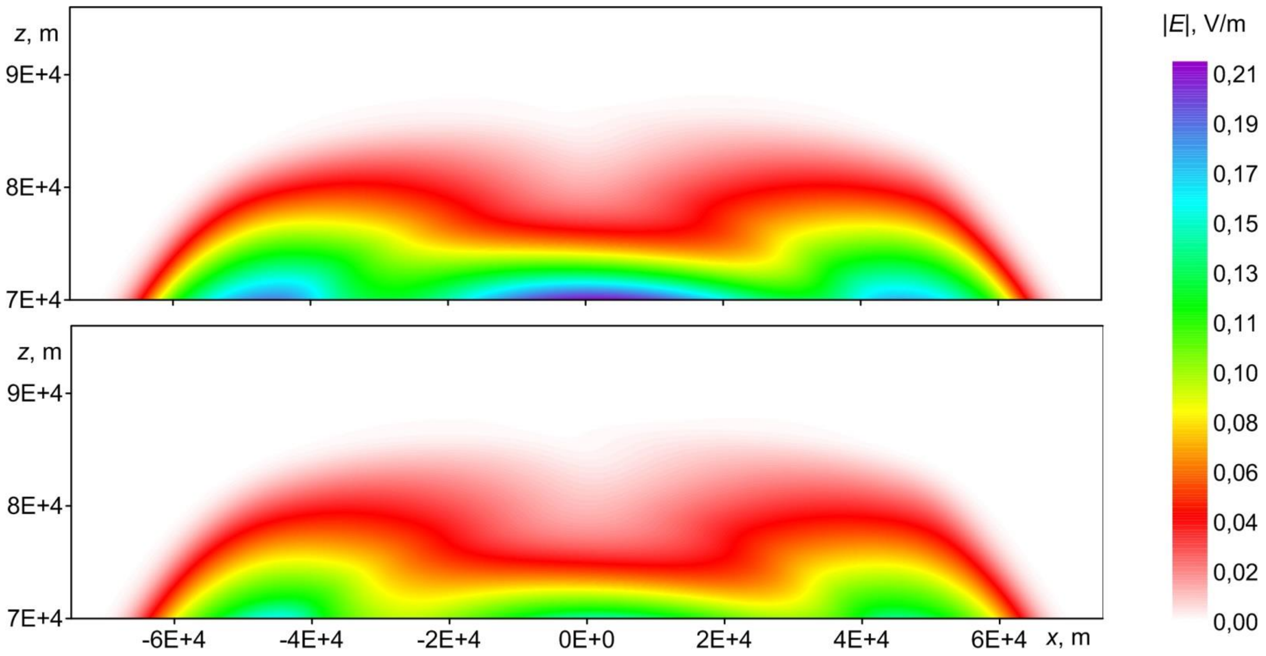

Fig.3. Vertical cross-sections of the electric field distribution over the symmetric cloud-to-ground discharge. The top and bottom panels represent distributions of the absolute values of the electric field and its transversal (normal to the magnetic field) component, respectively.

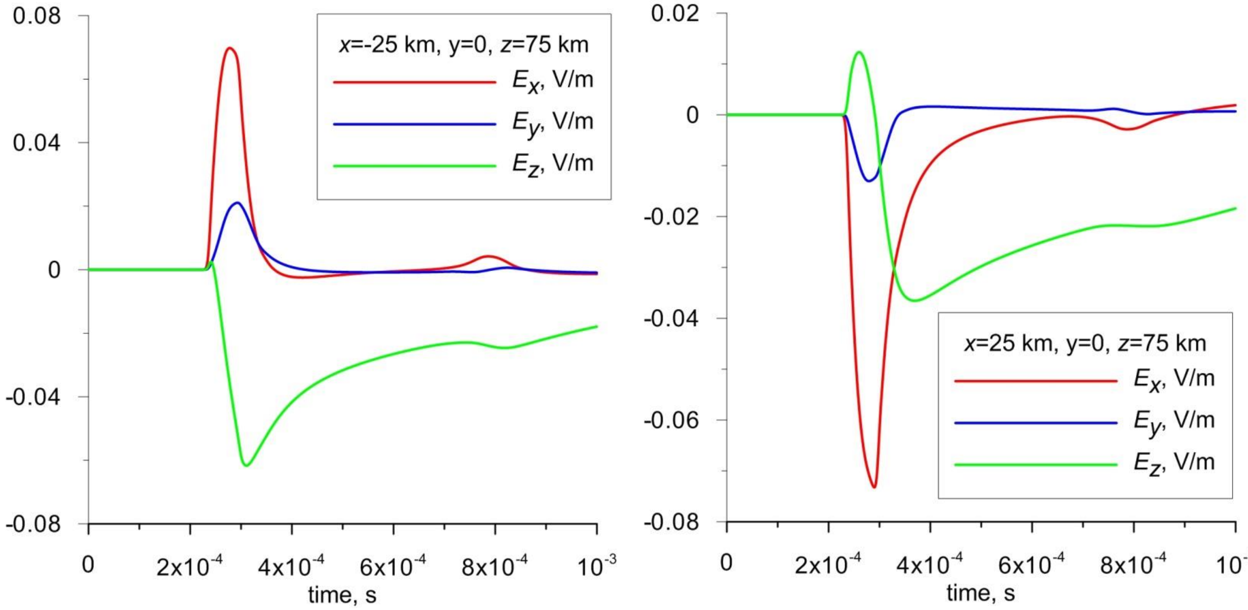

Fig.4. Temporal profiles of the electric field in two points at the height 75 km in the vicinity of the symmetric discharge. The points lie in the cross-section plane (see Fig.3) at the distance 25 km from the source axis.

CONCLUSIONS

The presented model describes both the quasistatic electric field and the electromagnetic pulse of a single lightning discharge in the plain atmosphere taking into account disturbance of the electric conductivity inside the thundercloud and anisotropy of the upper atmosphere. The model can be applied to solve both direct and inverse problems of the atmospheric electrodynamics. These are tightly connected with TLE modeling and retrieving information about the electric properties of the lightning discharge, in particular the temporal profile of the discharge current, location of the charged region(s) arisen due to the discharge, the disturbance of the electric conductivity inside the thundercloud.

ACKNOWLEDGMENTS

The work is supported in part by the Russian Foundation for Basic Research (projects 13-05-01100 and 13-05-97063) and the Government of the Russian Federation (contract 14.B25.31.0023).

REFERENCES

Davydenko, S. S., E. A. Mareev, A. S. Sergeev, and Yu. V. Shlyugaev, 2011: Modeling Atmospheric Electromagnetic Field Following a Lightning Discharge, *Proc. XIV Int. Conf. Atmospheric Electricity, 07-12 August, 2011, Rio de Janeiro, Brazil*, paper 229, 1-4.

Ma, Z., C.L. Croskey, and L.C. Hale, 1998: The electrodynamic responses of the atmosphere and ionosphere to the lightning discharge, *J. Atmos. Solar-Terr. Phys.*, **60(7-9)**, 845-861.

Mareev, E. A., S. A. Yashunun, S. S. Davydenko, T. C. Marshall, M. Stolzenburg, and C. R. Maggio, 2008: On the role of transient currents in the global electric circuit, *Geophys. Res. Lett.*, **35**, L15810, doi:10.1029/2008GL034554.

Marshall, R. A. , 2012: An improved model of the lightning electromagnetic field interaction with the D-region ionosphere, *J. Geophys. Res.*, **117**, A03316, doi:10.1029/2011JA017408.

Qin, J., S. Celestin, and V. P. Pasko, 2013: Dependence of positive and negative sprite morphology on lightning characteristics and upper atmospheric ambient conditions, **118**, 2623–2638, doi:10.1029/2012JA017908.