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SIMULATION STUDY OF LIGHTNING IMPACT ON THE GLOBAL ATMOSPHERIC ELECTRIC CIRCUIT OF VARYING PARAMETERS

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Abstract: *The global atmospheric electric circuit (GEC) is maintained by thunderstorms and electrified clouds. We study by modelling the DC response of GEC to a separate tropospheric electric source under quiet conditions and as a result of a lightning discharge. The phenomena in regional scale are considered first. The electric currents from a cloud into the ionosphere are studied depending on the geomagnetic latitude. The related electric fields can cause electron heating in the lower ionosphere, as well. Moreover, the post-lightning fields can produce a breakdown and red sprite. In global scale, a lightning discharge causes a transient variation of the ionospheric potential, which is evaluated here. The main global parameters of GEC are re-estimated.*

СИМУЛАЦИОННО ИЗСЛЕДВАНЕ РОЛЯТА НА МЪЛНИИТЕ В ГЛОБАЛНАТА АТМОСФЕРНА ЕЛЕКТРИЧЕСКА ВЕРИГА С ВАРИРАЩИ ПАРАМЕТРИ

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Ключови думи: *йоносферен потенциал, атмосферна проводимост, ток йоносфера-земя, наземен ток, гръмотевични бури, електрозаредени облаци, електронно нагряване, транзиентни събития на светене, спрайт.*

Резюме: *Глобалната атмосферна електрическа верига (ГЕВ) се захранва от гръмотевичните бури и електрозаредените облаци. Изследвана е моделно реакцията на ГЕВ, обусловена от отделен тропосферен източник на ток както при спокойни условия, така и в резултат на мълния. Отначало са разгледани проявите в регионален мащаб. Изследван е електрическият ток от облак към йоносферата на различни геомагнитни ширини. Установено е, че съответващото му електрическо поле в ниската йоносфера може да причини електронно нагряване. След мълния то може да доведе до диелектричен пробив и спрайт. Изследвана е глобалната вариация на йоносферния потенциал в резултат на мълния и е направена преоценка на някои глобални параметри на ГЕВ.*

Introduction

The thunderstorms (TS) and electrified shower clouds (ESC) in the Earth's troposphere are the electric sources in the global atmospheric electric circuit (GEC) which create a potential of ~250-300 kV of the ionosphere and an air-earth current of ~2 pA/m^{-2} [1-4]. A schematic layout of GEC is shown in fig.1. A complex and still incompletely understood system of links exists between: (a) TC/ESC, GEC, the cloud microphysics, the aerosols, the global temperature and climate, on one hand; and (b) the solar activity and space weather parameters, the galactic cosmic ray flux modulated by the solar wind, and other space factors, on the other hand. To investigate a part of this system, we study here the DC response of GEC to a single TS/ESC under different conditions. In regional scale we consider the electric currents and fields above a TS/ESC and their effects in the lower ionosphere, such as electron heating. We show that the electric currents flowing into the ionosphere, as well as the electron heating effect, depend significantly on the geomagnetic (gm) latitude. The transient variation of the ionospheric potential, as a result of a lightning discharge, is studied as a global scale response.

Quasi-static electric fields are also generated in the conjugated region of a lightning discharge. Estimation is made of the contribution of different types of electric currents in GEC.

Contribution of a TS / ESC in a regional scale

We present model results which reveal the role of TS / ESC in GEC with varying parameters. These results concern the DC aspect of GEC when by the space and time scales involved the electric and magnetic components can be considered as independent. First, we study the coupling of a single electric generator (TS or ESC) with the atmospheric regions above it in a regional scale. Some results which concern global scale DC interactions of a lightning to GEC are described in the next Section.

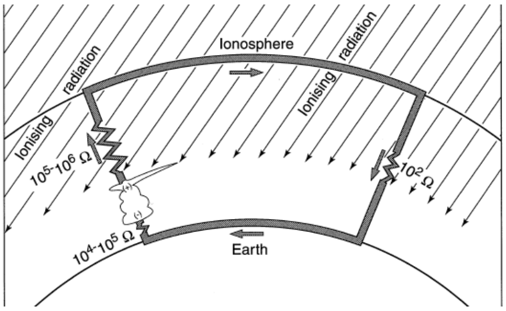

Fig. 1. Schematic view of the global atmospheric electric circuit represented as an equivalent circuit. In a region of TS / ESC upward electric current are generated. In fair-weather regions the currents are downward.

Our modeling is based on the continuity equation for the density of the electric current **j** whose source is a single TS or ESC by quiet conditions or during a cloud-to-ground (CG) lightning discharge:

$$\nabla \cdot \mathbf{j} = 0 \qquad (1)$$

Eq.(1) is used under two types of conditions:

1) In the steady-state case, when no lightning discharges are generated (slow changes of electric charges occur), Eq.(1) is for the conduction current $\mathbf{j} = \mathbf{j}_C = [\sigma]\mathbf{E}$, where $[\sigma]$ is the conductivity which is a tensor above 70 km.

2) During a CG lightning discharge in a TS Eq.(1) is for the full Maxwell current $\mathbf{j} = \mathbf{j}_M = \mathbf{j}_C + \mathbf{j}_D$, where $\mathbf{j}_D = \varepsilon_0 \partial \mathbf{E}/\partial t$ is the displacement current. The boundary conditions for Eq.(1) reflect that the surface is of infinite conductivity, compared to the adjacent air, and the parallel conductivity at a pre-determined ionospheric altitude can be considered as infinite (or tends to infinity). Above 70 km the conductivity tensor $[\sigma]$ significantly depends on the inclination (dip angle) I of the geomagnetic field.

First, we study the electric current which flow from a TS or ESC into the ionosphere at different gm latitudes. Fig.2a shows the boundary contours of 90% of the upward electric current which flows from an electrified cloud to the ionosphere, when the geomagnetic field is oriented vertically (assumed for high-middle latitudes). Three different conductivity profiles are used. Curves 1 and 2 are obtained for idealistic conductivity profiles by constant scale heights H = 4, and 5.5 km with no account of the anisotropy. Curve 3 corresponds to a realistic conductivity profile with respect to anisotropy. In this case the electric current at altitudes above 70 km tends to flow within a vertical tube with the increase of both the parallel conductivity and anisotropy. Fig.2b shows the electric current generated above a TS/ ESC at equatorial gm latitudes, where the geomagnetic field is horizontally oriented; the contours of the current are shown in a plain which is parallel to the equatorial plain. While the current

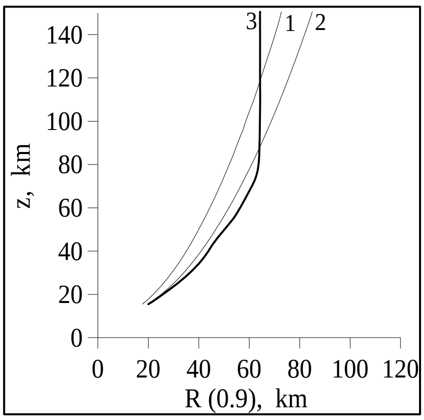

Fig. 2a. Contours of the upward electric currents generated by a TS/ESC at high latitudes which confine 90% of the total current for 3 conductivity profiles. Contours 1, 2 are obtained with no respect to anisotropy; it is taken into account only by contour 3.

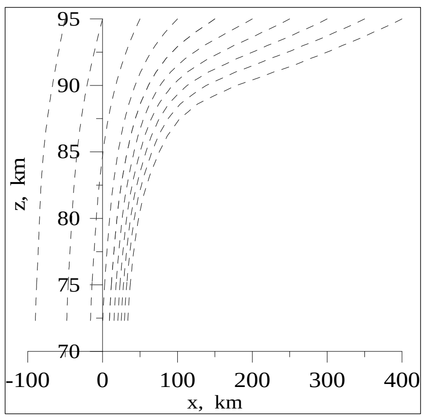

Fig. 2b. Contours of the electric current generated above a TS / ESC at equatorial gm latitudes in a vertical plane parallel to the equator. Below 75 km the current is predominantly upward, and above 75 km it becomes almost horizontal.

below 75 km is predominantly upward, above 75 km it is re-oriented as almost horizontal in west-east direction. This is an effect of the Hall conductivity which becomes significant above about 70 km.

The total current from a single TS / ESC to the ionosphere is estimated. In case (1) almost total current generated by the source is oriented to the ionosphere. This is shown below by the percentage of the upward current in the total current as a function of the scaled altitude of the source cloud charge (the ratio ζ_C of charge altitude to the conductivity scale height).

ζ_C	0.5	1.0	1.5	2.0	2.5	3.0
Upward current (%)	39	63	77	86	91	94

After a CG lightning discharge (type 2) much larger transient current to the ionosphere is produced. The peak current at 65 km reaches few kA [10]; its time scale is comparable to the local relaxation time (<~ 10^{-1} s).

Electric fields are also generated in GEC (in the lower ionosphere) in regional scale above a TS/ESC. The generated ones after a lightning discharge (the post-lightning fields) are much larger than those formed under quiet conditions. The electric fields are dramatically influenced by the gm latitude. Two cases of magnetic field orientation are considered again: (**a**) vertical, corresponding to high-middle latitudes; and (b) horizontal (at equatorial gm latitudes). Fig.3 shows a typical altitudinal dependence of the normalized dominating components of the electric field above an electric charge *Q* in a thundercloud in both cases. These results show that the electric field E above 75 km in case (**b**) is much larger than in case (**a**). Typical values for the ratio $R_{b/a}$ between the electric field intensities at altitudes 75 - 90 km above a thundercloud in cases (b) and (a) are given below:

Altitude, km	75	80	85	90
$R_{b/a}$	11.4	27.2	61.5	70.4

These steady-state electric fields can cause electron heating in the lower ionosphere above a thundercloud which leads to a decrease of the conductivity at night (in daytime such effects do not take place). This is demonstrated below for a specific nighttime conductivity profile by different effective cloud charge *Q* (50, 100, and 150 Coulombs) located at 15 km: the height intervals Z_5 and Z_{10} are given, where the conductivity reduction is at least 5 and 10 times, respectively:

Q, Coulomb	50	100	150
Z_5, km	76.8 - 81.6	75.3 - 82.1	73.2 - 82.6
Z_{10}, km	76.1 - 81.0	74.4 - 81.5	71.4 - 82.2

During and shortly after a lightning discharge (by conditions of type 2) the respective (post-lightning) electric fields are much stronger, than by quiet conditions (1), especially in the lower

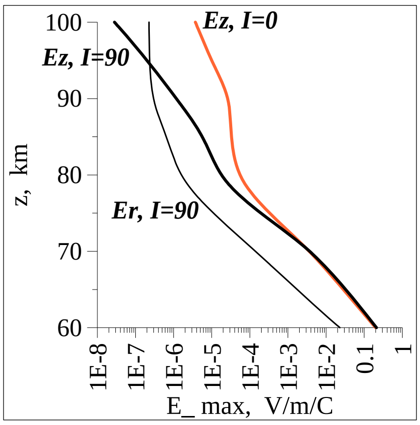

Fig.3. Vertical E_z and horizontal E_r normalized components of the electric field of a charge at altitude 15 km and constant by time in cases: (a) (*I*=90^0) and (b) (*I*=0^0).

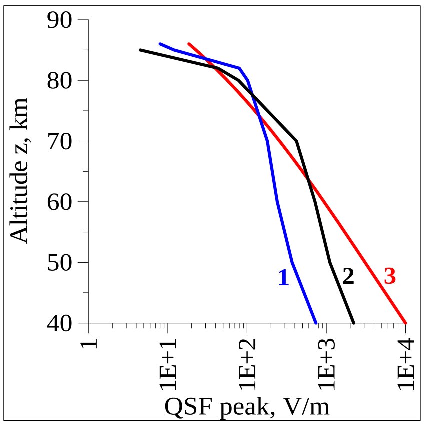

Fig. 4. Peak electric field as function of height by two types of CG lightning discharges: not accompanied (**1**) and accompanied (**2**) by continuing currents. Curve **3** is for the breakdown electric field.

ionosphere. This is demonstrated below by the ratio between the peak of the electric field E_{CG}(peak) due to a CG lightning discharge, and the field E (steady-state) before the discharge (by conditions 1).

Altitude, km	40	70	85	90
Ratio E_{CG}(peak) / E (steady-state)	16.8	187	1285	1490
Time of E_{CG} relaxation, s	2.1	2.7	0.25	0.012

Because of the big electric fields and of their relatively long relaxation, they possibly can cause a red sprite, e.g. [6]. It has to be mentioned that in the lower ionosphere the post-lightning electric fields, as well as their effects there, depend dramatically on the gm latitude, as shown in [9]: at equatorial gm latitudes they are much larger than at gm high-middle latitudes. The comparison between the peak electric field in cases (a) and (b) generated by the same source and by the same conductivity profiles gives similar results for the ratio between these peaks as the results obtained for steady-state conditions. The electric field is also significantly influenced by the parameters of the causative lightning discharge and of conductivity Fig.4 shows typical profiles of the vertical electric field E (the dominating component), which is generated after a CG lightning discharge in case (a) in two sample cases. Curves 1 and 2 correspond to +CG lightning discharges whose peak current are similar, but in the second case the discharge is characterized by continuing currents and long tail, as opposed to case 1. Fig.5 explains why the +CG discharges of type 2 are much better candidates for sprite-producing discharges than those of type 1. That is because the profile of the peak electric field has a knee at altitude where the relaxation time equals to the lightning discharge time. After +CG lightning with continuing currents the interval, where a breakdown is realized, comprises lower altitudes where the field is large enough for a long time to generate and maintain streamers in a proper timescale.

Besides, the spatial parameters of the region of electron heating in case (b) dramatically differ than those in case (a), as shown in [9]: in case (a) it has larger horizontal dimensions and is significantly shifted (up to many tens of kilometers) in east-west direction, compared to case (a).

The ionospheric potential V_I is a global characteristic of GEC, since the ionosphere is equipotential at gm latitudes below ~60^0. However, at higher gm latitudes the ionospheric potential is influenced by the ionospheric convection which determines a significant potential difference of 30-150 kV between the dawn and dusk sides of the polar cap by negative component B_z of the IMF [4]. Since this potential difference is a function of the solar wind parameters, it realizes a link between space weather and the atmospheric processes. This potential modification is mapped downward to GEC and the surface: it influences the air-earth current by ~20% and up to ~40 % by high solar activity [7].

We study the response of the background ionospheric potential V_I to a single CG lightning discharge. A model of the equivalent circuit (fig.1) is developed. Eq.(1) is transformed to a discrete representation for the Maxwell current in the equivalent circuit, in which separate segments are characterized by their resistor and capacitance. The results for the transient variation of the ionospheric potential V_I after lightning are shown in fig.5a,b, for a +CG and –CG lightning discharges, respectively, by an altitudes of the removed charge Z_C = 10 km and Z_C = 6 km. We see that the relative variation of the ionospheric potential by a single lightning discharge is rather small: 0.025% by +CG and 0.01% by –CG. A question arises whether the transient variation of V_I due to strongest +CG discharges can cause a measurable variation of the air-earth current and the potential gradient at the surface. If this is possible, this will serve as a confirmation of the Wilson's hypothesis.

We show in [8] that a +CG lightning discharge can cause a transient variation of the electric field in the conjugate region in the lower ionosphere and strato/mesosphere. The electric field intensity caused by a very strong lightning discharge (with a charge moment change 3500 C×km) in the conjugate region is 7.5×10^{-3}, 3.4×10^{-2}, 0.12, 0.02 V/m at altitude 90, 80, 70 and 60 km, respectively.

Further, estimations of the main GEC parameters are given based on a large number of studies (e.g. [1-3]) and on our results mentioned above.

Average surface Potential Gradient (PG):	PG = 100 - 120 V/m
Vertical conduction current density:	j_z = 2 - 3 pA/m2
Air conductivity at sea level:	$\sigma_{SL} = 2 - 3 \times 10^{-14}$ S/m
Ionospheric potential:	V_I = 250 - 300 kV
Total charge on the Earth's surface:	$Q_{TE} = -2\ -\ -5 \times 10^5$ C
Total resistance of the atmosphere:	R_T = 200 - 230 Ω
Total air-earth current:	J_T = 1000 - 1800 A
Average columnar resistance:	R_C = 120 pΩ.m^2
Mean global number of thunderstorms acting:	n_{TS} = 1000 - 2000

Time constant τ_G of GEC (i.e. the time for its discharging if there are no electric sources) is determined from the equation $J_T = dQ_{TE} / dt = -Q_{TE} / \tau_G$, i.e. $\tau_G = -Q_{TE} / J_T$ = 120 - 500 s with respect to the estimations of Q_{TE} and J_T. We adopt τ_G = 250 s (it is the geometric mean of minimum and maximum estimations), which agrees with [2].

Different types of currents flow in GEC, whose relative contribution has to be estimated. These types of currents are analyzed below:

1) Upward corona currents which flow from the ground (from sharp objects) up to the electrified clouds. According to the first studies [11], the total corona current J_{COR} over the globe is $J_{COR} = -100$ C.m^{-2}.year^{-1}, which is an overestimation. A partial estimation is obtained in [3] for the total corona current J_{COR-TC} below all thunderclouds: $J_{COR-TC}=10^3$ pA.m^{-2}. If the total area of the thunderstorms over the globe is 3×10^{11} m^2, as obtained in [2] (i.e. 0.06% of the Earth's surface), then J_{COR} has an average density ~ 0.6 pA.m^{-2} over the globe.

2) Upward currents due to negatively charged precipitations J_{PR} – these currents are generated below both TS and ESC with total area 2% of the Earth's surface. Their average density below the precipitating clouds is 45 pA.m^2, therefore their average density over the globe is 0.95 pA.m^2 [3].

3) Currents of the cloud-to-ground lightning discharges (intra-cloud discharges and those between clouds have no contribution in GEC). According to [5], their average density is 0.45 pA.m^2 by mean fair-weather current of 2 pA.m^2. The total current of these discharges depends on the relative contributions of the negative and positive CG discharges. Negative -CG discharges occur about ten times more often than the positive ones (+CG). However, the ratio between the total amount of charge transferred in both discharge types is 4:3, with respect to larger amount of charge removed by a +CG lightning discharge compared to a –CG one [3]. Having in mind that the global average rate of the lightning discharges is estimated to be ~50 s^{-1}, and the CG discharges are not more that 30% of all discharges, we conclude that the contribution of the CG lightning discharges in GEC is less than 10%. This estimation contradicts to the long-living idea that the CG lightning is the main source of the ionospheric potential. It shows, in agreement with [3], that the contribution of the CG lightning discharges by electric currents in GEC is small compared to the other current sources.

Some problems of the AC aspects of GEC

They are related to propagation of ELF/ VLF electromagnetic fields in the Ionosphere-Earth waveguide. A specific problem is the investigations of the Schumann resonances of this waveguide, which can serve as an indicator of global tropospheric characteristics as temperature and humidity. Assumingly, their main modes (~8, ~14 Hz) play an important role in controlling the α-wave frequency in human brains. Thus, SR can be a link between space weather and the health status of humans (e.g. cardio-vascular system, etc.). Commonly, the ELF / VLF waves can be used to indicate lightning discharges over the globe or to examine the disturbances in the D-region of the ionosphere. Their simulation is needed in the future, e.g. with the use of the FDTD method.

Conclusion

First, the electric currents and fields generated by a thunderstorm or an electrified cloud in regional scale by DC conditions are studied as part of investigating of the global atmospheric electrical circuit. We established that the upward currents from a cloud to the ionosphere depend particularly on the gm latitude. At equatorial gm latitudes a large east-west component of these currents is formed above 75 km, as opposed to high-middle latitudes where the currents flow in a vertical tube. The related electric fields are able to cause electron heating in the lower ionosphere by nighttime conditions above their source. This electric heating causes a decrease of the conductivity in the lower ionosphere up to several times. This is the effect by quiet conditions, when lightning discharges are missing. During and shortly after a +CG lightning discharge the electric fields in the lower ionosphere generated increase by 10^3 and more times and are able to cause a dielectric breakdown. These regional electric fields have a horizontal extent of 60-150 km in the lower ionosphere. Another localization where electric fields are generated after a lightning discharge is the magnetically conjugate region, in the lower ionosphere and mesosphere. However, these fields are much smaller than those at the same altitudes above the lightning discharge: from ~30% at 100 km to ~ 0.003% at 60 km.

A CG lightning discharge causes a transient modification of the ionospheric potential globally. Typically, it is an increase of few hundredths of percent by a cloud-ground lightning discharge.

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