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# ELECTROSTATIC RESPONSE OF ATMOSPHERIC REGIONS BY FAIR-WEATHER CONDITIONS TO DISTANT CLOUD-TO-GROUND LIGHTNING DISCHARGES

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***Abstract:*** *Time fluctuations of downward electric currents and fields generated in the global atmospheric electrical circuit (GEC) by fair-weather conditions due to strong cloud-to-ground lightning discharges (these last cause transient changes of ionospheric potential) are studied by modelling at different altitudes (particularly, at cloud tops and in mesosphere). These fluctuations may be a factor which enforces the link between solar variability and climate through a control on nucleation processes in clouds. At cloud tops these fluctuations are up to ~1%. In the mesosphere, by ambient conductivity profile, the superimposed electric fields can reach tens of mV/m*. However, if there are layers of highly reduced conductivity, such as in noctilucent clouds, these electric fields can be hundreds of mV/m or even of the order of V/m.

# ЕЛЕКТРОСТАТИЧНА РЕАКЦИЯ В ОБЛАСТИТЕ НА АТМОСФЕРАТА ПРИ ЯСНО ВРЕМЕ В РЕЗУЛТАТ НА ОТДАЛЕЧЕНИ МЪЛНИИ ОБЛАК-ЗЕМЯ

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***Ключови думи:*** *Атмосферно електричество, глобална електрическа верига, слънчева вариабилност, време и климат, моделиране*

***Резюме:*** *Изследвани са с помощта на моделиране времевите флуктуации на низходящите електрически токове в глобалната атмосферна електрическа верига (от ниската йоносфера към земята) във връзка с преходни вариации на йоносферния потенциал, възникващи при силни мълниеви разряди от тип облак-земя. Тези флуктуации могат да бъдат фактор, който влияе върху връзката между слънчевата вариабилност и климата чрез управлението на процесите на създаване на кондензационни ядра в облаците. На горната граница на облаците тези флуктуации са до ~1%. От друга страна, в мезосферата те са многократно по-големи – съответните преходни електрически полета могат да достигат, при несмутен профил на проводимост, десетки mV/m, а при наличие на слой с понижена прводимост, както в мезосферните облаци – и от порядъка на V/m.*

## Introduction

The global atmospheric electric circuit (GEC) is fed by the electric currents flowing upwards from the thunderstorms and electrified shower clouds located in the troposphere over the globe. As result, ionosphere has positive electric potential $V_I$~250-300 kV related to the ground. The closure of GEC is completed in regions of fair-weather conditions by the ionosphere-to-ground electric current $j_{fw}$~2 pA $m^{-2}$. At the level of cloud tops in the troposphere this current contributes to nucleation process in clouds, hence different factors, such as solar variability, could influence this process (and thus, weather and climate) by variations of $j_{fw}$ on different time scales [1]. This phenomenon is linked to formation of electrical charges at cloud tops because of the lower conductivity in clouds [2] compared to outer one. The ionosphere-to-ground current $j_{fw}$ is sensitive to the solar activity (SA) changes caused by modifications of GEC parameters due to changes in stratospheric conductivity $\sigma_S$ ($\sigma_S$ is formed by the galactic cosmic ray flux which is modulated by SA). During solar minimum the stratospheric conductivity is higher, i.e. the average downward electric current is bigger and has larger effects than during solar maximum. Here we study variations of the current $j_{fw}$ and related electric field $E_{fw}$ in time-scales much smaller than that of solar variability. Small time-scale variations of $j_{fw}$ are important with account to essentially nonlinear nucleation rate as function of $j_{fw}$. Here we estimate fluctuations of $j_{fw}$ at cloud tops, as well as at higher altitudes (in the mesosphere) which could arise due to fluctuations of the ionospheric potential $V_I$ caused by distant intense cloud-to-ground lightning discharges (CGLD). According to recent model studies [3, 4], the CGLD with large (>600 C km) charge moment change can cause transient modification of $V_I$ by up to few hundreds of Volts.

We propose a 1D model to study the quasi-static electrical response in GEC (represented by transient variations of $j_{fw}$ and $E_{fw}$) at different altitudes between the ionosphere and the cloud tops. Our results show that large transient changes of the ionospheric potential which arises due to sequences of intense CG lightning discharges can cause variations of the ionosphere-earth current $j_{fw}$ at cloud tops by up to almost 1%. In the mesosphere large vertical transient quasi-static variations superimposed on $j_{fw}$ and $E_{fw}$ are generated in layers with sharp conductivity gradient – the superimposed electric field $E$ can reach tens of mV/m. $E$ can be even several times larger as result of grouped intense lightning discharges. This is much better expressed in layers of dramatic reduction of conductivity, for example in noctilucent mesospheric clouds (NLC), where the electric fields $E$ can reach hundreds of mV/m, or much more by a sequence of several intense CGLD of the same polarity. Similar and even larger electric fields in the mesosphere have been systematically observed in rocket experiments. It should be noted, however, that other possible sources can take place in these cases, such as the ionospheric potential at auroral latitudes which exhibits large variations.

## Electric response of ionosphere and atmosphere to CGLD: model study

The effects of intense CGLDs on GEC in atmospheric regions with fair-weather conditions are considered. The average charge moment change for intense cloud-to-ground lightning discharges is ~1.6 kC km [5]. This corresponds to a mean magnitude of the charge transported by lightning ~160–320 C by typical lightning channel length ~5–10 km. The mean hourly global rate of intense positive SGLD (+CGLD) is ~1 per minute, and that of –CGLD is ~0.6 per minute for the diurnal peak at 16 LT [5]. From statistical view, the transient variation of the ionospheric electrical potential (IP) $V_I$ due to such intense CGLD will not be masked by the series of the rest much weaker (and of much larger rate) CGLDs of both polarities. According to [3], a typical moderate +CGLD causes transient IP decrease by ~40 V as shown in Fig.1 (the background IP is 300 kV). The rise time $t_{max}$ of $\Delta V_I$ to its peak $\Delta V_{Imax}$ is ~20 s; the relaxation time is ~400 s. More recent estimations [4] show that by the same conditions the peak IP change is twice as large. Following these estimations, the average $\Delta V_{Imax}$ due to an intense +CGLD, with account also to its channel length, will be ~400 V and can be much larger by an extremely intense +CGLD. With account to the global rate of the intense CGLDs, occasionally a sequence of several CGLDs grouped in time could cause several times larger peak $\Delta V_I$.

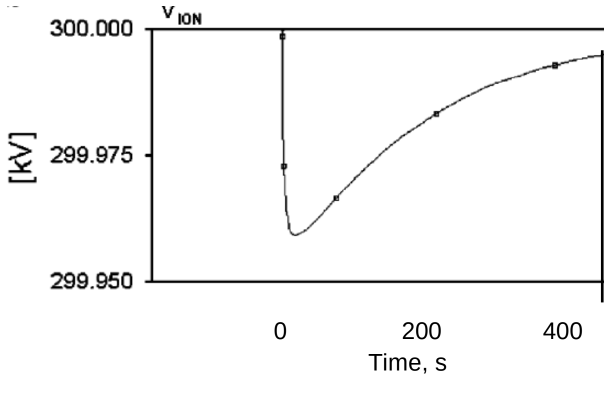

Fig. 1. GEC response to +CGLD with 67 C transferred represented by transient IP decrease [3]

We study the quasi-static response in GEC below the altitude $Z_I$ = 85 km assumed here to be the equalizing altitude at which the IP is $V_I$ = 300 kV. Since IP changes in Fig.1 are much faster than those at lower altitudes due to the increase of conductivity $\sigma(z)$ with height, the capacitive properties of the medium are involved. The Maxwell's current between ionosphere and ground is $\mathbf{j}_M = \mathbf{j}_{const} + \mathbf{j}_c + \mathbf{j}_d$

where $\mathbf{j}_{const} = j_{fw}$ is the DC fair-weather current generated by the background IP $V_I$ = 300 kV which is constant by altitude $z$, $\mathbf{j}_c$ and $\mathbf{j}_d$ are the conduction and displacement currents superimposed on $\mathbf{j}_{const}$ due to IP transient variation $\Delta V_I(t)$. A time-dependent 1D model is developed assuming stratified conditions so that the characteristics are functions of altitude $z$ and time $t$. For $\mathbf{j} = \mathbf{j}_c + \mathbf{j}_d$ we have:

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

$\mathbf{j}_c = \sigma E$, $\mathbf{j}_d = \varepsilon_0\, dE/dt$; $E(z,t)$ is the superimposed potential electric field. From (1) we obtain for $E$:

(2) $$\frac{d}{dz}\left[\sigma E + \varepsilon_0 \frac{dE}{dt}\right] = 0$$

Eq.(2) is solved with initial and boundary conditions: $E(z,t=0) = 0$ ; $\int_0^{Z_I} E(z,t)dz = 0$ .

Eq.(2) is solved numerically in order to obtain variations of the Maxwell's current $j_M$ at cloud tops, as well as in the mesosphere. Estimations are made for a case when a group of +CGLDs cause IP variation with $\Delta V_{Imax}$= 1 kV. After rise to its peak $\Delta V_{Imax}$, the IP transient variation relaxes exponentially with characteristic time 400 s (to agree with the results in Fig.1). This time scale is close to the relaxation time of electrical charges at the ground level. The response of the atmospheric regions below 85 km is estimated for two nighttime conductivity profiles: *i*) Profile [6] composed from data obtained experimentally and theoretically, and *ii*) Profile based on data from rocket measurements above the Wallops island obtained in [7].

Firstly, we examine the relative change of the electric current superimposed to the background fair-weather current $j_{fw}$ at altitudes corresponding to the tops of clouds (Table 1) for peak IP change $\Delta V_{Imax}$ (the mean $\Delta V_{Imax}$ value for intense +CGLDs, as estimated above). Conductivity profile [7] is used. Three cases are considered for the reduction coefficient of conductivity $\sigma_{cl}$ in the cloud compared that out of the cloud $\sigma_{out}$. According to [2] the $\sigma_{out}$ is several times larger than $\sigma_{cl}$. In the first two rows in Table 1 cases of 3- and 10-fold reduction of cloud conductivity are considered. In general, the reduction coefficient may be as large as 50 – this case is represented in the last row. It is important to take into account also the thickness of the layer of transition from conductivity $\sigma_{out}$ at the cloud top boundary $z(\sigma_{out})$ to the reduced conductivity $\sigma_{cl}$ inside the cloud (altitude $z(\sigma_{cl})$ in Table 1). This thickness varies here from 200 m for the first case down to 50 m for the third case; it determines the sharpness of the $\sigma$ gradient.

Results are obtained for the relative variation (in %) of the conduction current $j_c$ at the cloud top related to the fair-weather current $j_{fw}$. We note that the ratio $j_c / j_{fw}$ dramatically increases when the cloud top is at higher altitude (i.e. by larger conductivity $\sigma_{out}$), when bigger reduction of the cloud conductivity (related to the adjacent) takes place, and for sharper gradient in the transition layer from $\sigma_{out}$ to $\sigma_{cl}$. Also, the rise time $t_{max}$ to the peak magnitude of the superimposed current conduction $j_c$ decreases with the increase of the cloud top altitude. Similar feature takes place for the relaxation time of the current $j_c$. The interpretation of these results is that IP changes on a given timescale cause variations in the fair-weather current $j_{fw}$ only down to the level where the relaxation time is comparable to this timescale.

Table 1. Transient electric field variations in mesosphere by transient IP change –400 V

| Cloud top, km | $\sigma_{out} / \sigma_{cl}$ | $z(\sigma_{out}) - z(\sigma_{cl})$, m | $j_c / j_{fw}$, % | $t_{max}$, s | $t_{relax}$, s |
|---|---|---|---|---|---|
| 5 | 5 | 200 | –0.072 | 19 | 160 |
| 10 | 10 | 100 | –0.12 | 11 | 95 |
| 15 | 50 | 50 | –0.42 | 8.6 | 78 |

The electrical response in the mesosphere to transient variations of IP $V_I$ due to intense CGLD is examined (Table 2) in three cases where conductivity profiles [3] and [4] are adopted. An extreme IP disturbance of –1 kV is used in these cases which can be a result of several +CGLDs which occur almost simultaneously. The electric field $E$ superimposed to background DC field $E_{fw}$ is examined. E is shown at altitudes $z_{max}$ where it reaches maximum $E_{max}$ at time $t_{max}$. These characteristics are given in Table 2 together with the time of relaxation of the electric field $E$. In the first two cases undisturbed conductivity profiles ii) and i) are assumed. $E_{max}$ in these cases is reached close to the layer of abrupt conductivity change for each $\sigma$ profile. In these cases $E_{max}$ is tens of mV/m. In the third case a presence of a nuctilucent cloud (NLC) is assumed: it occupies a thin layer above 80 km as shown in Table 2. It is characterized by very large reduction of the conductivity in it.

Table 2. Transient electric field variations in mesosphere by transient IP change of −1 kV

| Conductivity profile | NLC layer | $\sigma_{\min}$ in NLC | $E_{\max}$, V/m | $z_{\max}$, km | $t_{\max}$, s | $t_{\text{relax}}$. s |
|---|---|---|---|---|---|---|
| *ii*) [7] | - | - | −0.028 | 68 | 0.03 | 0.26 |
| *i*) [6] | - | - | −0.059 | 72 | 0.02 | 0.14 |
| *i*) [6] | 82-82.8 km | $5.10^{-11}$ S/m | −0.77 | 82.4 | 0.03 | 0.25 |

These results that the electric fields in the NLC can be of the order of 1 V/m. Similar large electric fields in fair-weather mesosphere have been experimentally observed by a series of scientists [8]. Even much larger fields have been found in such experiments, as well, as these shown in Fig.2 [9]. The question whether such large electric fields are result of transient IP variations due to intense CGLDs is still open: there can be other sources, for example, much larger transient IP variations at auroral latitudes related to the solar wind and the ionospheric convection. Possibly, large mesospheric fields could be created locally also due to CGLD in the magnetically conjugate region.

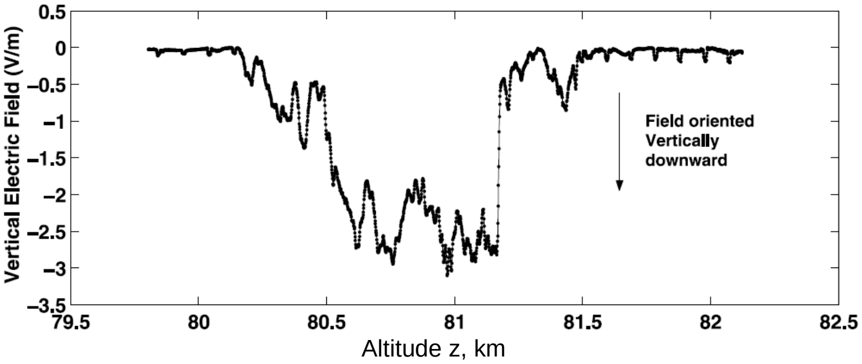

Fig. 2. Experimental data of the vertical electric field in an NLC [9]

## Conclusion

Variations of the electric currents and fields in global electric circuit at cloud tops and in the mesosphere caused by ionospheric potential fluctuations due to intense cloud-to-ground lightning discharges are studied. At cloud tops in the troposphere fluctuations up to ~1 % of the fair-weather electric current can take place. In the mesosphere with undisturbed conductivity. fluctuations of the vertical electric fields of tens mV/m and more can be realized; superimposed electric fields of tenths of V/m could be generated close to layers with abruptly changing conductivity. Generation of even larger electric fields (of the order of 1 V/m) can be generated within nuctilucent clouds with highly reduced conductivity.

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