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Charge transfer to the ionosphere and to the ground during thunderstorms

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[1] This study examines the current that is driven to the ionosphere and to the ground before, during and after single negative cloud-to-ground (CG) and intracloud (IC) lightning discharges. A numerical model has been developed, that calculates the quasi-electrostatic field before the lightning, due to the slow accumulation of the charge in the thundercloud, and after the lightning by taking into account the Maxwellian relaxation of charges in conducting atmosphere and accounting for the dissipation stage of the thunderstorm development. From these results, the charges that are transferred to the ionosphere and to the ground are calculated. We demonstrate the significance of considering the pre-lightning and the dissipation stages and accounting for realistic distribution of the conductivity inside of the thundercloud for the accurate calculation of the charge flow to the ionosphere and to the ground. We show that the charge transfer to the ionosphere depends mainly on the altitudes of the charges inside of the thundercloud and on their spatial separation. The amount of charge that is transferred to the ground, due to currents flowing in the vicinity of the thundercloud during a transient time period following a lightning discharge, is significantly affected by the conductivity distribution in the thundercloud and can be several times smaller than the amount of charge that is transferred to the ionosphere during the same time period.

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1. Introduction

[2] The Global Electric Circuit (GEC) is a circuit that is formed between the Earth's surface, which is a good conductor of electricity, and the ionosphere, a weakly ionized plasma at ~80 km altitude [e.g., *Rycroft et al.*, 2008]. In the absence of any source, the GEC behaves as a leaky spherical capacitor, with the ground being the negative charged plate and the ionosphere the positive charged one, which discharges through the weakly conducting atmosphere creating fair-weather current which is about 1 kA integrated over the entire Earth's surface [e.g., *Bering et al.*, 1998].

[3] *Wilson* [1921] first suggested that thunderstorms are the main generators in the GEC and this concept was supported by early measurements and statistical analysis of several thunderstorms [*Brooks*, 1925] along with above-cloud measurements [*Gish and Wait*, 1950].

[4] In *Holzer and Saxon* [1952] an analytical thunderstorm model was developed for steady state conditions and it was shown that the conduction currents that are generated by concentrated charge centers in the conducting atmosphere have sufficient amplitude to support the fair-weather current of the global circuit.

[5] *Illingworth* [1972] computed the recovery time of the electric fields due to lightning as a function of the location of the charge centers using a numerical time-dependent model. It was shown that the electric field recovery curves at the ground due to lightning depend on the distance from the storm and are a result of the redistribution of the induced charge in the atmosphere.

[6] *Dejnakarintra and Park* [1974] showed that higher frequency components of the electric field produced by lightning could be transmitted to the ionosphere more efficiently than lower frequency components. They also suggested that lightning can induce localized electric fields in the middle-altitude ionosphere and magnetosphere.

[7] *Hays and Roble* [1979] modeled thunderstorms as positive and negative pairs of quasi-static point current sources, and concluded that large scale thunderstorms maintain the large electric potential difference between the ionosphere and the Earth, and produce electric currents that flow through the magnetosphere along geomagnetic field lines.

[8] *Makino and Ogawa* [1984] used the results that were derived by *Hays and Roble* [1979] regarding the total upward current of the bipolar point current sources, averaged the upward thunderstorm currents and used these average currents as sources in the GEC.

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[9] *Tzur and Roble* [1985] developed a quasi-static numerical axisymmetric model with a detailed electrical conductivity profile and viewed the thundercloud as a volumetric dipole distribution of negative and positive charge centers. This model was the first model capable of resolving small-scale phenomena in the vicinity of the thundercloud.

[10] In *Few et al.* [1988] the integrated upward current, I_{up}, from thunderstorms and multicell thunderstorm complexes was computed. It was shown that because of the strong geometric divergence of the electric fields above the sources and the strong divergence of current in the ionosphere, the middle atmosphere region, 30–50 km, appears to be the most promising region in which to measure the contribution of thunderstorms and thunderstorm complexes to the global electric circuit.

[11] *Driscoll et al.* [1992] demonstrated that a simple analytical expression derived from the continuity equation of the electric current, can express thunderstorm's average current contribution to the global electric circuit in terms of the generator current within the thundercloud, the intracloud (IC) lightning current, the cloud-to-ground (CG) lightning current, the altitudes of the charge centers and the conductivity profile of the atmosphere.

[12] In *Stansbery et al.* [1993] an axisymmetric numerical model in an Earth-centered spherical coordinate system was created to calculate the electric field distribution and current distribution from a thunderstorm source in the global electric circuit. The model included a hemisphere in which the thunderstorm was located, an atmosphere and ionosphere with anisotropic height-variable conductivities, and a passive magnetic conjugate hemisphere. The current output from the thunderstorm spreads out in the ionosphere and flows along the magnetic field lines into the conjugate hemisphere. Results show that approximately half of the current that reaches the ionosphere flows into the conjugate hemisphere, and the rest is redirected to the fair-weather portion of the storm hemisphere. Thus, it is important to include a realistic model of the ionosphere to evaluate the spread of current in the ionosphere and the mechanism of thunderstorm charging of the global electric circuit. We note that *Stansbery et al.* [1993] studied the electric potential distribution throughout the global atmosphere caused by a thunderstorm generator. The model is focused mainly in the Wilson currents by considering a constant source current (which may represent the charge separation current that electrifies the cloud or the corona current below the cloud) and by calculating the steady state solutions for the slow charge separation phase. The lightning is considered by approximating the steady state calculations of the gross effects of lightning by a local conductivity perturbation that prevents excessively high electric fields from developing. As already mentioned above, the main results of this work show that half of the current (Wilson current) flowing into the ionosphere travels to the passive magnetic conjugate hemisphere and half of this current generates a downward fair-weather current far from the cloud region in the storm hemisphere. We emphasize that in our work, we focus on the charge that is transferred to the ionosphere and to the ground in the immediate vicinity of the thunderstorm before and after the occurrence of a lightning, and we do not quantify the amount of the ionospheric charge that is transferred to the magnetic conjugate hemisphere or to the ground in fair-weather regions.

[13] In *Davydenko et al.* [2004] a layered system of external currents was used to model the electrical environment of a Mesoscale Convective System (MCS), in order to determine the electric field and the current inside and in the vicinity of a stationary MCS as well as the net vertical current above the thunderclouds. These authors showed that the relatively large horizontal scale of an MCS ensures a more effective coupling to the ionosphere than for an isolated thunderstorm and that an MCS can serve either as an effective generator in the global circuit or as a discharger of it depending on the polarity, magnitude and thickness of the layers of the external currents. In accordance with *Davydenko et al.* [2004] the term "external current" represents an effective current flow without describing the actual physical current or its means of generation. Most of the external currents are located inside the MCS [*Davydenko et al.*, 2004].

[14] *Marshall et al.* [2005] presented balloon-borne data which show that slow transients of cloud-to-ground lightning discharges (CG) act as generators of the global circuit and slow transients of intracloud lightning discharges (IC) discharge the global circuit.

[15] In *Rycroft et al.* [2007] the commercially available computer program PSpice was used for the simulation of upward currents that close through the global electric circuit and which are driven by several processes acting below, in and above thunderstorms and electrified shower clouds. The electric potentials and fields at specific points in the global electric circuit were calculated, before, during and after CG lightning flashes of either negative or positive polarity, and also following a sprite discharge. Knowing the global average rate of lightning discharges, it was found that negative CG discharges increase the ionospheric potential by ~4%, and that positive CG discharges reduce it by ~3%. It was concluded that the net upward current to the ionosphere due to the lightning is ~20 A and that the conduction and convection currents associated with "batteries" within thunderclouds and electrified shower clouds contribute essentially equally (~500 A each) to maintaining the ionospheric potential.

[16] *Mareev et al.* [2008] developed a numerical model of the transient electric field due to CG and IC flashes and their Maxwell relaxation (slow transients) and calculated the electric field, the current distributions, the decay time of the electric field and the total charge that is transferred to the ionosphere and to the ground. Defining the efficiency of the charge transfer to the ionosphere process as the ratio of the total charge transferred to the ionosphere to the net charge neutralized during the lightning, they showed that typical CG flashes have efficiencies of 55–75% and typical IC flashes 5–15%.

[17] In *Maggio et al.* [2009a] the above-cloud charge transfers due to lightning transients were estimated for five IC and five CG flashes from four thunderstorms that occurred in New Mexico, USA in 1999, using in-cloud and above-cloud electric field data from balloons, ground-based electric field data, and Lightning Mapping Array data. For the five CG flashes (which transferred -4 to -13 C to the ground), the transient currents moved +1 to +5 C of charge upward from the cloud toward the ionosphere, with an average transient charge transfer of about 35% of the charge transferred to the ground. For the five IC flashes (which neutralized 6 to 21 C inside the cloud), the transient currents

moved −0.7 to −3 C upward, with an average charge transfer of about 12% of the lightning charge. Estimates for three thunderstorms indicated that the transient currents made only a small contribution to the global electric circuit compared to the quasi-stationary Wilson currents because of the offsetting effects of IC and CG flashes in these storms [*Maggio et al.*, 2009a].

[18] *Rycroft and Odzimek* [2010] constructed a quantitative model of the global electric circuit using the PSpice electrical engineering software package, mentioned above in the context of previous work of *Rycroft et al.* [2007]. The circuit consists of currents (∼1 kA) above thunderstorms and electrified rain/shower clouds that raise the potential of the ionosphere (equipotential surface at 80 km altitude) to ∼250 kV with respect to the Earth's surface, and is completed by currents flowing down through the fair weather atmosphere in the land/sea surface and up to the cloud systems. Using a model for the atmospheric conductivity profile, the effects of both positive and negative CG lightning discharges on the ionospheric potential have been estimated. Moreover, estimates have been made of the return stroke current and the thundercloud charge moment change of a positive CG discharge required to exceed the threshold breakdown field, or the threshold field for creating and sustaining negative or positive streamers. It was also found that the current flowing in the highly conducting sprite reduces the ionospheric potential by ∼1 V. We emphasize, that this estimate indicates a negligible contribution of a single sprite event to the global electric circuit.

[19] In the present paper, we use a model similar to that of *Mareev et al.* [2008] but we employ a more realistic profile for modeling the conductivity inside of the thundercloud and we take into consideration the quasi-electrostatic fields before the CG and IC flashes, due to the slow accumulation of the charge in the thundercloud. We also model the late dissipation stages of the thunderstorm development. We show the significant role that the pre-lightning and the dissipation stages play in the charge transfer to the ionosphere and to the ground and demonstrate how these factors affect the efficiencies of charging the global electric circuit calculated in previous publications.

2. Physical Mechanism

[20] The physical mechanism of the contribution of the thunderstorms to the global electric circuit can be described as follows. In the absence of a thunderstorm there is a current that flows between the ionosphere and the ground (fair weather current) due to the potential difference between these two surfaces.

[21] As a thundercloud is created, several physical processes lead to its electrification. In these processes charges are supplied to the thundercloud by either external sources (fair weather space charge and corona near the ground and cosmic rays near the cloud top) and/or by collisions between precipitation particles (graupel) and cloud particles (small ice crystals) [e.g., *Rakov and Uman*, 2003, pp. 84–88]. The fact that the electrical conductivity inside of the thundercloud has a very low value, because atmospheric ions quickly attach to cloud particles [e.g., *Riousset et al.*, 2010, and references therein], favors the accumulation of charge. As charge is accumulated inside of the thundercloud and is separated in several charged layers, charge is induced in the conducting surrounding air around the cloud. This process creates currents that flow toward the ionosphere and to the ground and thus there is a charge transfer to these surfaces. Only a fraction of the induced charge is deposited to the ionosphere and to the ground.

[22] During a lightning discharge, charge is removed from the thundercloud or neutralized. This charge removal/neutralization creates an excess of charge of specific polarity (depending on the type of the lightning discharge). The excess of the charge creates an electric field in the vicinity of the ionosphere. Because of this field, charge of opposite polarity with respect to the excess charge is induced in the conducting atmosphere and moves toward the excess charge, and charge of the same polarity as the excess charge is transferred to the ionosphere. So, out of a specific amount of removed/neutralized thundercloud charge a fraction is induced and moves toward the excess charge and a fraction is deposited to the ionosphere.

[23] In *Mareev et al.* [2008] it was explained that due to the conservation of charge the net amounts of charge transferred to the ionosphere and to the ground due to the combined fast (lightning discharge) and slow (after lightning) transient stages are equal in magnitude and opposite in polarity, and they represent the real flash contribution to the global electric circuit. The term of efficiency was introduced which is the amount of charge that is transferred to the ionosphere over the amount of charge removed/neutralized by a lightning discharge. In this paper, following a similar concept we define efficiency as the amount of charge that is transferred to the ionosphere over the absolute value of the maximum charge that is accumulated in the thundercloud. Considering that the global electric circuit can be seen as a capacitor whose positive plate is the ionosphere and the negative plate is the ground, positive value of the efficiency means a transfer of additional positive charge to the ionosphere which leads to the charging of the system and negative value of the efficiency means a transfer of negative charge to the ionosphere which leads to the discharging of the system. The introduction of the efficiency helps us to quantify the contribution of a thunderstorm to the global electric circuit. The efficiency represents a fraction of the charge created inside of the thundercloud that leads to the charging or discharging the global electric circuit.

3. Model Formulation

[24] In our model we use a quasi-static two-dimensional approach to calculate the electric field before, during and after CG and IC flashes, and the resultant charges that are transferred to the Earth and to the ionosphere. We treat the quasi-electrostatic fields as the slowly varying and long enduring electric component of the total electromagnetic field which is generated by the removal of charge from the cloud, neglecting any short-duration electromagnetic pulses generated mainly by the return stroke currents. These quasi-electrostatic fields are established in the mesosphere and lower ionosphere due to the accumulation of thundercloud charge and its evolution in time as a portion of this charge is

removed from the cloud due to a CG lightning or neutralized in the cloud due to an IC discharge.

[25] A cylindrical two-dimensional coordinate system (r, z) is used, with the z- axis representing the altitude. The system is considered to be symmetric about the z- axis. The ground (z_0 = 0 km), upper ($z_{\max}$ = 40 km) and the side (r = 80 km) boundaries are assumed to be perfectly conducting. The choice of the upper boundary is justified by the fact that the current flow between 40 km and the ionosphere is mainly vertical [e.g., *Mareev et al.*, 2008], and several simulations with the upper boundary positioned at higher altitudes indicate that the relative difference between the results does not exceed ~3%. The choice of the radial distance for the side boundary introduces an error less than 10% in the vicinity of the boundary for the calculation of the potential [e.g., *Pasko et al.*, 1997]. This error decreases as one approaches the center of the simulation domain. We emphasize that the charge flow through the side boundary is at least 2 orders of magnitude lower than the charge flow through the upper and bottom boundaries and thus the choice of r = 80 km does not affect the results of the current analysis.

[26] The thundercloud charges $\pm Q$ (also named source charges in this paper) form a vertical dipole, which is assumed to develop over a time τ_f = 400 sec. The negative charge or both the negative and positive charges, in the case of negative CG flashes and IC flashes, respectively, are then removed linearly in time by decreasing the magnitude of the charge to zero within a time interval τ_s = 400 msec. This value of τ_s was chosen to be equal to ~3 times the relaxation time (i.e., ϵ_0/σ) at the maximum altitude of the simulation domain, so that numerical errors that appear because of the sudden charge removal can be avoided. This chosen τ_s value does not affect any conclusions of the present work. After the lightning, the source charges either remain constant until the end of the simulation, or are allowed to dissipate in the conducting atmosphere due to the gradual increase of the thundercloud conductivity to ambient pre-thunderstorm values (see discussion below).

[27] For the case of a negative CG lightning, the continuous thundercloud charge distribution dynamics can be represented in the following mathematical form:

$$\rho_s(r,z,t) = f_+(r,z)\frac{t}{\tau_f} + f_-(r,z)\frac{t}{\tau_f}, \quad 0 \le t \le \tau_f$$
$$\rho_s(r,z,t) = \rho_s(r,z,\tau_f) - f_-(r,z)\frac{t}{\tau_f+\tau_s}, \quad \tau_f < t \le \tau_f + \tau_s$$
$$\rho_s(r,z,t) = \rho_s(r,z,\tau_f+\tau_s), \quad \tau_f + \tau_s < t$$

where $f_\pm(r, z)$ are the spatial distributions of the positive and negative charges. The $f_\pm(r, z)$ in the present work are considered to be Gaussian of the following form:

$$f_\pm(r,z) = \frac{Q_\pm}{(2\pi)^{3/2}\alpha_z\alpha_r^2}\exp\left(-\frac{(z-h_\pm)^2}{2\alpha_z^2} - \frac{r^2}{2\alpha_r^2}\right)$$

where α_z = 1 km and α_r = 1 km are the vertical and horizontal scales of the charge distributions, $h_\pm$ are the altitudes of their centers and $Q_\pm = \pm 1$ C are the total values of the positive and negative charges that are deposited/removed to/from the system. We note at this point, that the chosen value of 1 C for the source charges is much less than the required amount of charge for the lightning discharge initiation. However, because of the linearity of the problem, this low charge value can be scaled to realistic values without affecting the efficiency values that have been calculated (the amount of the charge that is transferred to the ionosphere will be multiplied by the same scale factor and thus the ratio of the amount of charge that is transferred to the ionosphere over the amount of positive charge that is accumulated in the thundercloud will be the same).

[28] For the case of an IC lightning the corresponding mathematical expression that describes the dynamics of the thundercloud charge distribution is as follows:

$$\rho_s(r,z,t) = f_+(r,z)\frac{t}{\tau_f} + f_-(r,z)\frac{t}{\tau_f}, \quad 0 \le t \le \tau_f$$
$$\rho_s(r,z,t) = \rho_s(r,z,\tau_f) - f_+(r,z)\frac{t}{\tau_f+\tau_s} - f_-(r,z)\frac{t}{\tau_f+\tau_s},$$
$$\tau_f < t \le \tau_f + \tau_s$$
$$\rho_s(r,z,t) = 0, \quad \tau_f + \tau_s < t$$

[29] The temporal variation of the source charges produces time and space-varying induced charges ρ_f and electric potentials ϕ inside and outside the thundercloud. The set of equations that relates the quantities ρ_s, ρ_f, ϕ and $\mathbf{E}$ are given by Poisson's equation and the charge conservation equation:

$$\nabla^2\phi = -\frac{\rho_t}{\epsilon_0} \tag{1}$$

$$\frac{\partial\rho_t}{\partial t} - \nabla\sigma\cdot\nabla\phi = -\sigma\frac{\rho_t}{\epsilon_0} \tag{2}$$

$$\mathbf{E} = -\nabla\phi \tag{3}$$

where σ is the atmospheric conductivity and $\rho_t = \rho_s + \rho_f$ is the total charge density. In the above equations the conduction current $\mathbf{J}$ is defined as $\mathbf{J} = \sigma\mathbf{E} = -\sigma\nabla\phi$.

[30] The conductivity $\sigma(r, z)$ at any location of the simulation domain is expressed similarly to *Riousset et al.* [2010] as follows:

$$\sigma(r,z) = \underbrace{\sigma_0 e^{z/l}}_{(I)}\underbrace{\left(1 - \frac{1-\tanh\left(\frac{r-r_c}{\alpha}\right)}{2}\times\frac{1-\tanh\left(\frac{z-z_c}{\alpha}\right)}{2}\right)}_{(II)} \tag{4}$$

where $\sigma_0 = 5\times10^{-14}$ S/m is the conductivity at ground level, l = 6 km is the altitude scaling factor, z_c = 20 km and r_c = 20 km are the vertical and horizontal extents of the cloud, and α = 800 m is the thickness of the conductivity transition region between the cloud and the surrounding air. The values for the z_c and the r_c are chosen large enough so that there is no mixing between the charges in the thundercloud and the charges that are induced on its boundaries. The width of the transition boundary α, between the inner cloud and the surrounding atmosphere can be small. Small values of α can lead to instabilities in the numerical scheme and errors. That's why we choose a value that ensures a numerically smooth transition between the inner cloud and the outer atmosphere and minimizes the numerical error (~2%), so that in practical calculations the transition region

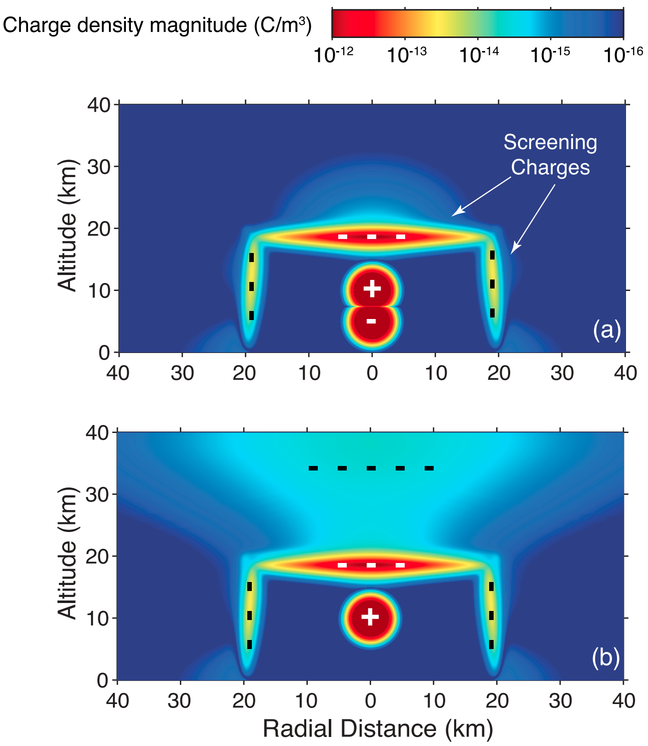

Figure 1. Charge dynamics in the case of a negative CG lightning with $Q_{\pm} = \pm 1$ C, at altitudes $h_+ = 10$ km and $h_- = 5$ km. (a) Cross-sectional representation of the charge distribution right before the lightning ($t = 400$ sec). (b) Cross-sectional representation of the charge distribution right after the lightning ($t = 400.4$ sec).

contains 5 to 8 grid points. The term (I) represents the conductivity profile of the surrounding to the cloud atmosphere and it is appropriate for altitudes less than 60 km where the total conductivity is dominated by the ion conductivity [e.g., *Pasko et al.*, 1997, and references therein]. For higher altitudes, where the total conductivity is dominated by the electron conductivity, term (I) should be appropriately modified [e.g., *Riousset et al.*, 2010]. Moreover a proper scaling should be applied for different time intervals during diurnal cycle, since the conductivity profile changes between daytime and nighttime [e.g., *Rakov and Uman*, 2003, p. 9]. The term (II) is introduced to express the fact that inside the cloud the electrical conductivity has very low value because atmospheric ions quickly attach to cloud particles [e.g., *Riousset et al.*, 2010, and references therein].

[31] The so defined conductivity distribution effectively leads to a zero conductivity value inside the thundercloud. This assumption is adopted from previous modeling [*Krehbiel et al.*, 2008; *Riousset et al.*, 2010] and does not significantly alter the principal conclusions of the current work. In the framework of the present modeling, the chosen conductivity model allows to explicitly highlight the effects of low conductivity inside of the thundercloud. Effects of more accurate conductivity distributions will be discussed in dedicated future studies.

[32] Because of the low conductivity inside the thundercloud, after the completion of the transient processes related to the lightning discharge there is an amount of volumetric charge left between the ionosphere and the ground (some of it is located inside the thundercloud as the remaining charge after a CG lightning discharge, and some of it is distributed at the boundaries of the thundercloud). In order to study the contribution of the dissipation phase of the thunderstorm development to the global electric circuit, we add an additional phase during which we linearly increase the conductivity inside the thundercloud during a time interval equal to 450 sec to the value of the conductivity of the surrounding atmosphere. This additional phase can be seen as the cloud relaxation which takes place at the end of the thunderstorm evolution. In this way, we can quantify the contribution of the whole thunderstorm evolution to the global electric circuit. All the charges that are created during the several stages of the thunderstorm will either be neutralized due to the IC lightning and due to the existence of the conducting medium or will be transferred to the ionosphere and to the ground (either due to CG lightning or due to the conducting currents). As clearly mentioned above, at the end of the entire thunderstorm evolution equal amounts of charge of opposite polarity are expected to be deposited to the upper (ionosphere) and lower (ground) boundaries [*Mareev et al.*, 2008].

[33] Having defined σ by equation (4), we solve the system (1)–(3) for the three unknowns ϕ, $\mathbf{E}$ and ρ_f. Poisson's equation (1) is solved using the Successive Overrelaxation Method (SOR), while the continuity equation is solved using the Two-Step Lax-Wendroff scheme. Finally, the charges transferred to the ground and the ionosphere are calculated by integrating the conducting current over horizontal planes, corresponding to the lower and upper boundaries.

4. Results

4.1. Negative CG Lightning Case

[34] Figure 1 illustrates the charge dynamics in the case of a negative CG flash. The positive charge is assumed to be located at $h_+ = 10$ km, the negative charge is assumed to be at $h_- = 5$ km and both charges $Q_{\pm} = \pm 1$ C are generated in the thundercloud during a period of 400 sec. The electric potential at the center of the positive thundercloud charge at the end of 400 sec is ~5.4 MV and at the center of negative thundercloud charge is ~ -5.1 MV. The positive charge is located at higher altitude than the negative one and negative screening charge is induced at the upper boundary of the thundercloud due to the response of the conducting atmosphere to the imposed charge configuration. At the end of the charge accumulation stage and because of the dimensions of the cloud, negative charge is induced around the thundercloud (Figure 1a). We note that if the radial width of the thundercloud was decreased, the positive charge would be induced at the lower half part of the side boundary. The results for the pre-lightning phase and for the IC flash case do not depend on the choice of the radial width. On the other hand, the results for the CG flash case have a strong dependence on the choice of the radial width of the thunderclound. If the radial width is chosen to be 10 km instead of 20 km, then the charge that is transferred to the ionosphere during the CG flash stage is increased by ~28% and the charge that is transferred to the ground is increased by ~74%. After the occurrence of the lightning and the removal of the negative charge of the

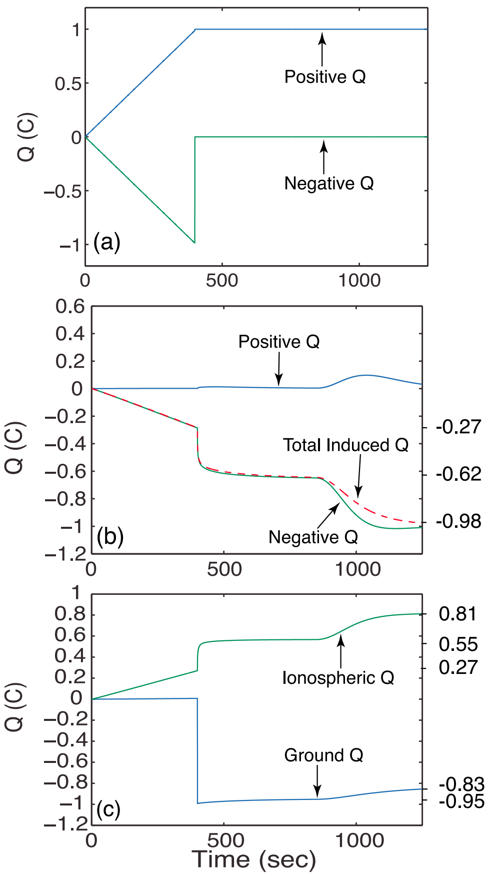

Figure 2. Charge dynamics in the case of a negative CG lightning with $Q_{\pm} = \pm 1$ C, at altitudes $h_{+} = 10$ km and $h_{-} = 5$ km. (a) Time dynamics of the source charges. (b) Time dynamics of the volumetric induced charge. (c) Charge transferred to the upper and lower boundaries.

thundercloud, the excess of positive charge leads to the appearance of additional negative screening charge at higher altitude (Figure 1b). This induced charge at the end of the relaxation stage is distributed around the thundercloud. Both the remaining positive charge inside the thundercloud and the induced charge that is distributed at the thundercloud boundaries dissipate completely during the cloud relaxation phase.

[35] Figure 2a shows the evolution of the charges inside the thundercloud. During the first 400 sec, the source charges are accumulating linearly in time inside the thundercloud up to the value of 1 C. Then the negative charge is removed because of the lightning and the positive charge remains until the end of the simulation (i.e., 1250 sec). On the other hand, negative charge is induced around the thundercloud during the charge accumulation stage and then, after the lightning, further negative charge is induced which is distributed around the thundercloud (Figure 2b). Note that the induced charge does not reach the value of −1 C at the end of 850 sec, because it can not “enter” the thundercloud, and is merely a response of the conducting atmosphere to the electric field at some distance from the source charge. During the last stage of the simulation and the relaxation of the cloud, as conductivity increases, more charge is induced and eventually the total induced charge is equal to −0.98 C which is opposite and is only 2% lower than the remaining positive source charge in the cloud (the total induced charge is not equal to −1 C because more time beyond 1250 sec is required for the complete relaxation of the thundercloud). The charge that is transferred to the ionosphere due to Wilson current during the slow charge accumulation stage is equal to +0.27 C while the charge that is transferred to the ground is almost equal to zero. After the lightning occurs, the additional charge that is transferred to the ionosphere is equal to +0.28 C and the charge that is transferred to the ground is equal to −0.95 C (−1 C because of the lightning discharge and +0.05 C during the relaxation process after the lightning occurrence) (Figure 2c). Finally, during the thundercloud dissipation phase +0.26 C are transferred additionally to the ionosphere and +0.12 C are transferred to the ground. At the end of the simulation both ionosphere and the ground have the same amount of charge which is equal to 0.81 C (the small difference of +0.02 C which remains in the volume between the ionosphere and the ground at $t = 1250$ sec will eventually go to the ground and will be added to −0.83 C that are present at the end of the simulation). So eventually the system will be charged with an amount of charge equal to 0.81 C, and the efficiency of this model thunderstorm with a single CG lightning discharge and with charges located at the given altitudes is 0.81 (or 81%). If we sum up the charges inside the thundercloud, the charges that are induced in the atmosphere and the charges that are transferred to the upper and lower boundaries at every time step, then we find that the total charge is zero, which ensures the conservation of the charge in the system. As a result of the scenario discussed above, the GEC will be charged with an amount of charge equal to +0.81 C at the ionosphere and −0.81 C on the ground.

[36] We note that the charge that is transferred to the ionosphere after the occurrence of the lightning (+0.54 C) is ~2 times larger than the charge that is transferred during the electrification phase of the thunderstorm (+0.27 C), and that the charge that is transferred to the ground after the lightning discharge (+0.17 C) is only 17% of the charge that is transferred directly to the ground due to the lightning (−1 C).

[37] *Mareev et al.* [2008] used a simpler model to calculate the charge that is deposited to the ionosphere and to the ground after the lightning. They did not take into account the difference in conductivity between the interior part of the thundercloud and the surrounding atmosphere and they used an equivalent model (which was discussed in *Pasko et al.* [1997] in the context of modeling of high altitude transient luminous events called sprites) to study the effects of the lightning. According to this model, the charge removal caused by the lightning can be viewed as a “placement” of an identical charge of opposite sign. This means that the negative CG lightning can be modeled as a deposition of an equal amount of positive charge at the same altitude as the negative charge that is removed by the lightning.

[38] Figure 3 shows the time evolution of the charge dynamics for the case of a CG lightning derived from the model that was presented by *Mareev et al.* [2008]. At the beginning 1 C of positive charge is deposited at altitude equal to 5 km. Then the system is allowed to relax for a period of 450 sec. Figure 3a shows the evolution of the

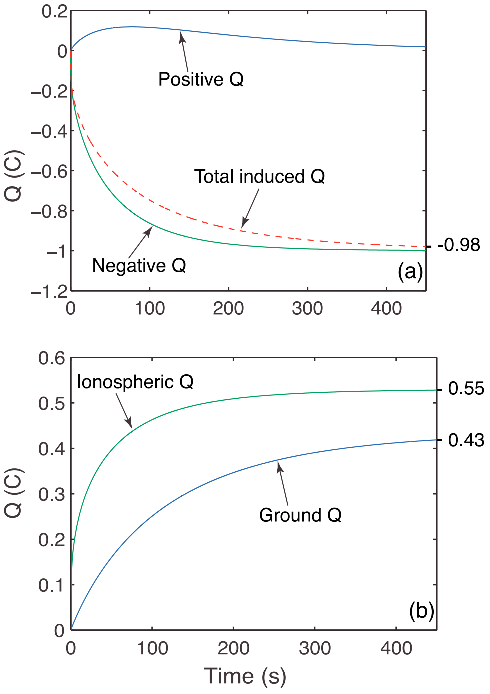

Figure 3. Charge dynamics in the case of a negative CG lightning calculated using the equivalent model of *Mareev et al.* [2008]. (a) Time dynamics of the volumetric induced charge. (b) Charge transferred to the upper and lower boundaries.

volumetric induced charge. At the end of the simulation, the induced charge is −0.98 C and it has screened almost completely the deposited positive charge, since in this model there is no low conductivity cloud region that limited the charge relaxation in the previous model case. Figure 3b shows the charge that is deposited to the upper and to the lower boundaries. The conservation of charge dictates that the total amount of the charge that is deposited to the boundaries is equal to the total amount of charge that it is induced in the atmosphere. At the end of the simulation the total amount of charge that is deposited to the boundaries is equal to 0.98 (there is a small amount of charge equal to 0.02 C which remains in the simulation domain because of the long relaxation time at the ground), which is indeed the amount of charge that is induced in the atmosphere. From this amount of +0.98 C, +0.55 C are deposited to the upper boundary and +0.43 C are deposited to the lower boundary (the remaining +0.02 C that are left in the simulation domain will eventually be transferred to the ground, so the total charge on the ground will be +0.45 C).

4.2. IC Lightning Case

[39] Figure 4 shows the time evolution of the charge dynamics in the case of an IC lightning. The positive charge is assumed to be located at $h_{+} = 10$ km, the negative charge is assumed to be at $h_{-} = 5$ km and both charges $Q_{\pm} = \pm 1$ C are generated in the thundercloud during a period of 400 sec. The dynamics and distribution of the screening charges in Figure 4a are identical to that discussed with relationship to Figure 1a. After the occurrence of the lightning and the neutralization of the charges inside the thundercloud, the excess of negative charge leads to the induction of positive charge at higher altitudes (Figure 4b). This induced charge at the end of the relaxation stage is distributed around the existing negative charge at the boundaries of the thundercloud. These remaining charge layers at the boundaries of the thundercloud are eventually neutralized completely during the cloud dissipation phase.

[40] Figure 5a shows the evolution of the charges inside the thundercloud for the IC lightning case. During the first 400 sec, the source charges are accumulating linearly in time inside the thundercloud up to the value of 1 C. Then the charges are neutralized because of the lightning and no charge remains in the cloud until the end of the simulation. On the other hand, negative charge is induced around the thundercloud during the charge accumulation stage and then, after the lightning, positive charge is induced which is distributed around the thundercloud and screens the existing negative charge (Figure 5b). Note that although the total net volumetric induced charge at the end of the 800 sec is equal to zero, there are 0.04 C of positive and 0.04 C of negative charge that form two layers at the boundary of the cloud. These charges will be eventually neutralized during the cloud dissipation stage. The charge that is transferred to the ionosphere during the slow (pre lightning) charge accumulation stage is equal to +0.27 C while the charge that is transferred to the ground is almost equal to zero. After the lightning occurrence the negative charge of

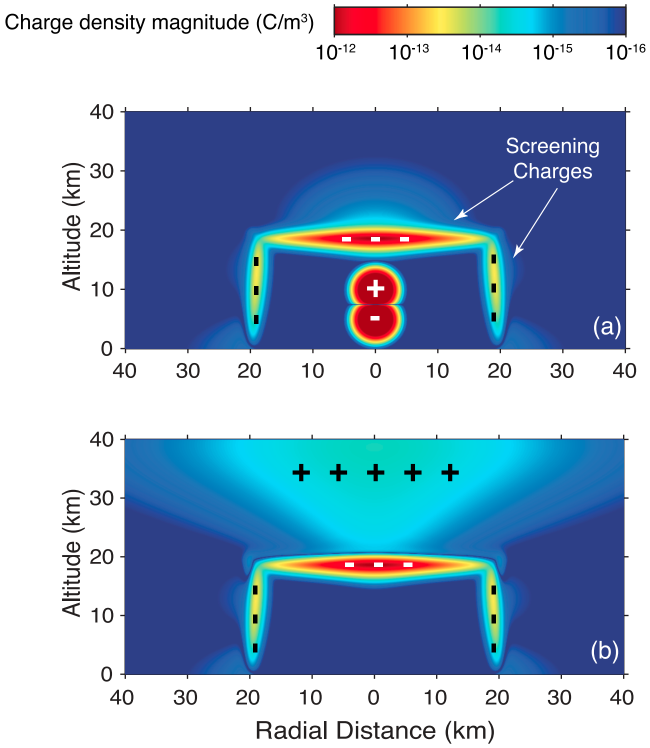

Figure 4. Charge dynamics in the case of an IC lightning with $Q_{\pm} = \pm 1$ C, at altitudes $h_{+} = 10$ km and $h_{-} = 5$ km. (a) Cross-sectional representation of the charge distribution right before the lightning ($t = 400$ sec). (b) Cross-sectional representation of the charge distribution right after the lightning ($t = 400.4$ sec).

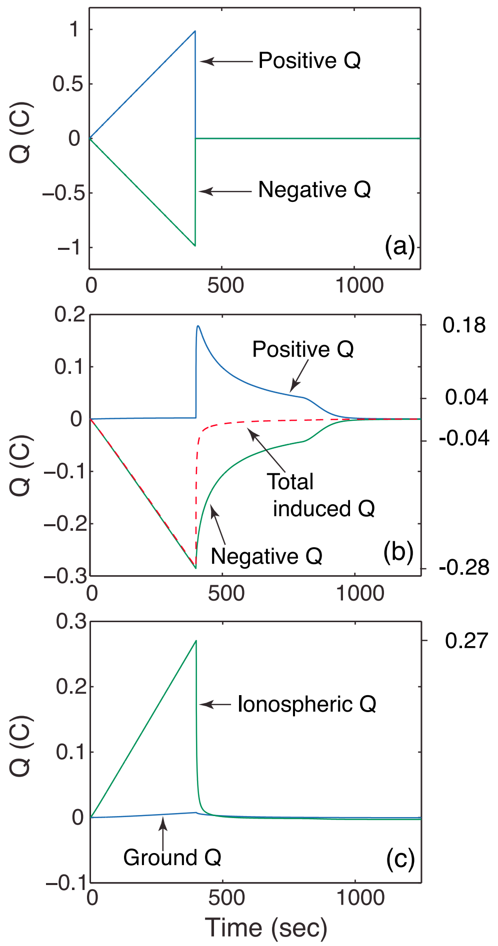

Figure 5. Charge dynamics in the case of an IC lightning with $Q_\pm = \pm 1$ C, at altitudes $h_+ = 10$ km and $h_- = 5$ km. (a) Time dynamics of the source charges. (b) Time dynamics of the volumetric induced charge. (c) Charge transferred to the upper and lower boundaries.

−0.27 C is transferred to the ionosphere (because positive charge is induced and is deposited around the thundercloud). The charge that is transferred to the ground is again equal to zero (Figure 5c). We note that during the cloud dissipation phase a very small (negligible) amount of charge is transferred to the ionosphere. The total charge that was deposited to the ionosphere and to the ground during the entire thunderstorm evolution with a single IC lightning discharge discussed above is zero, and thus the efficiency of this thunderstorm is zero, which means that this thunderstorm does not contribute to the global electric circuit. Similarly to previously considered cases, if we sum up the charges inside the thundercloud, the charges that are induced in the atmosphere and the charges that are transferred to the upper and lower boundaries at every time step, then we find that the total charge is zero, which ensures the conservation of the charge in the system.

[41] Figure 6 illustrates the time evolution of the charge dynamics for the case of an IC lightning derived from the model that was presented by *Mareev et al.* [2008]. The neutralization of the positive and negative charges that occurs during an IC lightning can be viewed using the equivalent model as a deposition of the same amount of negative and positive charges at respective altitudes. At the beginning 1 C of negative charge is deposited at altitude equal to 10 km and 1 C of positive charge is deposited at altitude equal to 5 km. Then the system is allowed to relax for a period of 450 sec. Figure 6a shows the evolution of the volumetric induced charge. At the end of the simulation, 0.99 C of positive charge and 0.98 C of negative charge have been induced and have screened the deposited charges. Figure 6b shows the charge that is deposited to the upper and to the lower boundaries. The conservation of charge dictates that the total amount of the charge that is deposited to the boundaries is equal to the total amount of charge that it is induced in the atmosphere. At the end of the simulation the total amount of charge that is deposited to the boundaries is equal to 0.01 C which is indeed the amount of the induced charge that is present in the atmosphere. We note that −0.22 C are deposited to the upper boundary and +0.23 C are deposited to the lower boundary and 0.01 C is the difference between these charge amounts. The total induced charge is not zero at the end of the simulation because of the slow relaxation rate of the atmosphere at the ground. Eventually this amount of charge will be transferred to the ground.

4.3. Dependence on the Altitude of the Source Charges

[42] Figure 7 describes results of simulations when two charges of ±1 C are slowly generated (deposited) in the thundercloud. This figure illustrates the dependence of the charge transferred to the ground and to the ionosphere on the altitude of the positive charge (Figure 7a) and on the altitude of the negative charge (Figure 7b). In Figure 7a, we

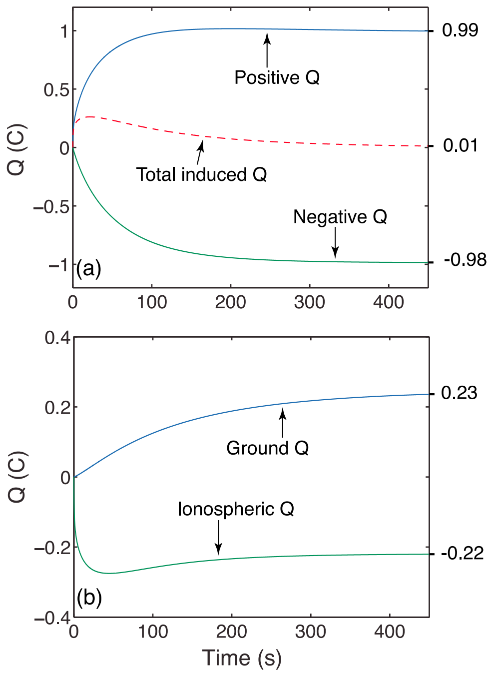

Figure 6. Charge dynamics for the case of an IC lightning calculated using the equivalent model of *Mareev et al.* [2008]. (a) Time dynamics of the volumetric induced charge. (b) Charge transferred to the upper and lower boundaries.

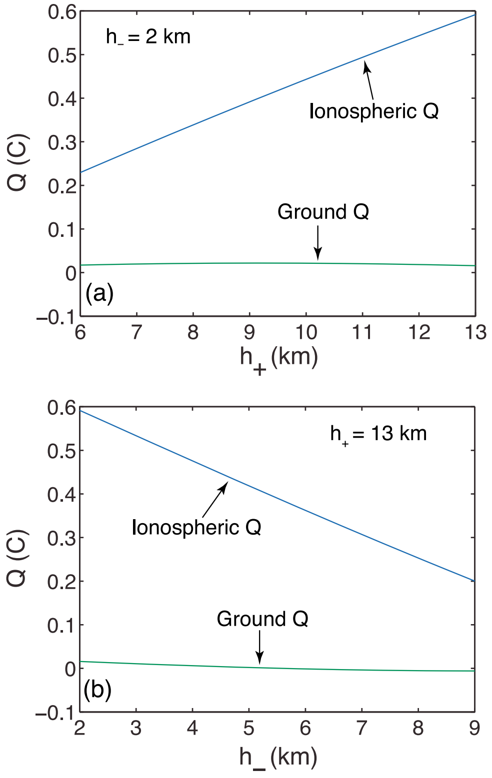

Figure 7. Charges transferred to the ground and to the ionosphere at the moment right before the occurrence of a lightning ($t = 400$ sec) as a function of (a) h_+ with $h_- = 2$ km and (b) h_- with $h_+ = 13$ km. The charges at that time are equal to $Q_\pm = \pm 1$ C.

see that while the altitude of the deposited positive charge increases, the transferred charge to the ionosphere also increases because the electric field is stronger at higher altitudes due to the presence of the positive charge. On the other hand in Figure 7b, we see that while the altitude of the deposited negative charge increases, the transferred charge to the ionosphere decreases. This happens because as the negative charge comes closer to the positive charge, the electric field gets stronger in the area between them and decreases in the area between the positive charge and ionosphere. From these results we can conclude that the charge transfer to the ionosphere during the cloud electrification phase depends on the spatial separation of the accumulated charges and it ranges between 0.2 C and 0.59 C. For the chosen thundercloud conductivity model, the amount of charge that is transferred to the ground is one order of magnitude less than the amount of charge that is transferred to the ionosphere, it depends mainly on the altitude of the negative charge and it ranges between −0.006 C and 0.022 C.

[43] Figure 8 shows the charge transferred to the ionosphere and to the ground after a CG flash (for the case of removal of −1 C) as a function of the altitude of the positive charge (Figure 8a) and the altitude of negative charge (Figure 8b). We note that in contrast to Figure 2c, the charge deposited to the ground shown in these graphs does not include the −1 C transferred by the negative CG and therefore illustrates the net deposition of the charge to the ground due to the flow of the conduction current following the lightning discharge. For the case of the negative CG flash, the charge that is transferred to the ionosphere is almost independent on the altitude of the positive charge. Figure 8a shows that if the altitude of the positive charge is increased by 7 km (116%) , the charge that is transferred to the ionosphere is increased by 3%. On the other hand, the charge that is transferred to the ionosphere depends mainly on the altitude of the negative charge that is removed (Figure 8b). From Figure 8 it can be seen that the charge that is transferred to the ionosphere ranges between 0.11 C and 0.495 C. Similarly to the previous case (i.e., Figure 7), the transferred charge to the ground is approximately one order of magnitude less than the charge that is transferred to the ionosphere, it depends on the altitude of the removed negative charge as well as the distance between the positive and the negative charge and it ranges between 0.022 C and 0.042 C.

[44] Figure 9 shows the charge transferred to the ionosphere and to the ground after an IC flash (for the case of neutralization of ±1 C) as a function of the altitude of the positive charge (Figure 9a) and the altitude of negative charge (Figure 9b). From these figures it is clear that the charge that is transferred to the ionosphere due to an IC flash depends mainly on the distance between the removed positive and negative charges (the larger the distance, the larger the amount of charge that is transferred) and it ranges between −0.2 and −0.6 C. The charge that is transferred to

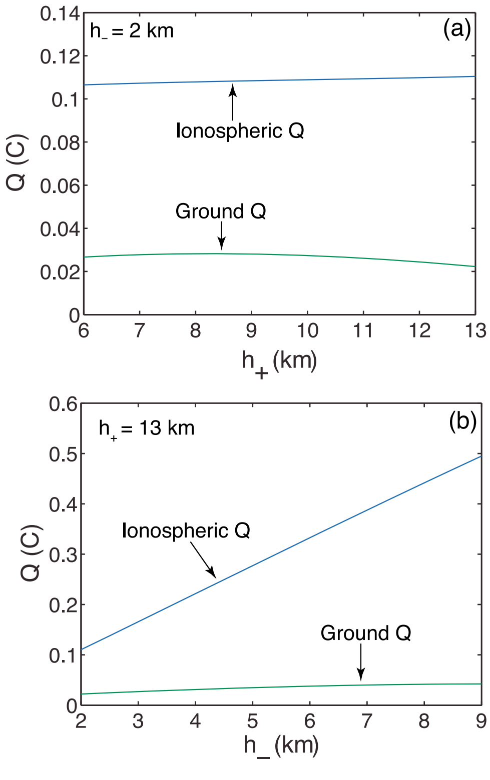

Figure 8. Charges transferred to the ground and to the ionosphere 450 sec after the occurrence of a negative CG lightning ($t = 800$ sec) as a function of (a) h_+ with $h_- = 2$ km and (b) h_- with $h_+ = 13$ km. These charges represent the deposited charges to the ground/ionosphere because of the removal of −1 C of negative charge from the thundercloud.

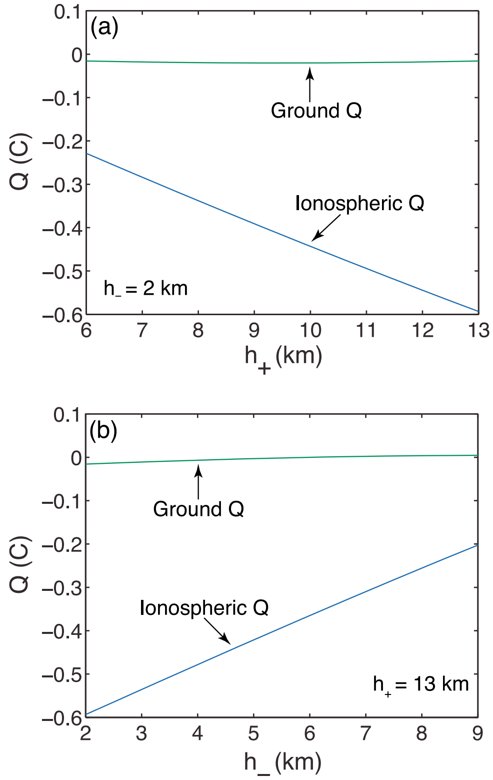

Figure 9. Charges transferred to the ground and to the ionosphere 450 sec after the occurrence of a IC lightning (t = 800 sec) as a function of (a) h_+ with h_- = 2 km and (b) h_- with h_+ = 13 km. These charges represent the deposited charges to the ground/ionosphere because of the neutralization of −1 C of negative charge with 1 C of positive charge in the thundercloud.

the ground is negligible compared to the charge that is transferred to the ionosphere, it depends mainly on the altitude of the removed negative charge and it ranges between −0.02 C and 0.004 C.

[45] It is important to emphasize that for the IC case the positive charge transferred to the ionosphere during the pre-lightning phase (Figure 7) is exactly compensated by the negative charge deposition following the lightning (Figure 9) so that IC discharge does not contribute to the GEC, consistent with results shown in Figure 5c (when the accumulated source charges are completely neutralized by the IC lightning discharge).

[46] The results of Figures 7–9 show that the charge that is transferred to the ionosphere during a thunderstorm, changes linearly with the charge moment (i.e., charge multiplied by altitude) of the placed/removed charges to/from the thunderstorm. *Rycroft et al.* [2007] reached a similar conclusion and specifically they concluded that the ionospheric potential changes linearly with the charge moment related to a negative CG lightning discharge.

[47] Figure 10 shows results for a negative CG case in terms of the charge transfer to the ionosphere and to the ground at the end of the cloud dissipation phase as a function of the altitude of the remaining positive charge. We note that this stage corresponds to the last +0.26 C deposition to the ionosphere and +0.13 C to the ground between ~800 sec and 1250 sec time evolution, corresponding to the negative CG scenario shown for h_+ = 10 km in Figure 2c. From Figure 10 it is clear that the charge that is transferred to the ground decreases as the altitude of the remaining positive charge increases. At the same time, the charge that is transferred to the ionosphere initially increases as the altitude of the remaining charge increases, but as the remaining positive charge approaches the upper boundary of the thundercloud, the charge that is transferred to ionosphere starts decreasing. Thus we can say that the charge that is transferred to the ground depends on the altitude of the remaining charge inside the thundercloud and the charge that is transferred to the ionosphere depends on the altitude of the remaining charge as well as its distance from the upper boundary of the thundercloud. We also note that during this phase of the thunderstorm the charge that is transferred to the ground is not negligible compared to the charge that is transferred to the ionosphere and for some smaller h_+ values is up to two times larger.

4.4. Dependence on the Conductivity Profile

[48] Figure 11 shows the charge that is transferred to the ionosphere and to the ground for the case of a negative CG lightning for two different conductivity profiles. For the first profile the term (I) of equation (4) has $\sigma_0 = 5 \times 10^{-14}$ S/m and scale height l = 6 km [*Dejnakarintra and Park*, 1974], while for the second profile the term (I) has $\sigma_0 = 6 \times 10^{-13}$ S/m and scale height l = 11 km [*Holzworth et al.*, 1985] (Figure 11a). For both of these two profiles the term (II) is the same. The second profile has lower values at high altitudes than the first profile and thus the charge that is transferred to the ionosphere is lower (Figure 11b). On the other hand, the second profile has larger values for low altitudes and thus the charge that is transferred to the ground is larger than in the case of the first profile. For the conductivity profile 1 the altitude at which the electric field becomes vertical is ~40 km (thus the upper boundary of the simulation domain is set at

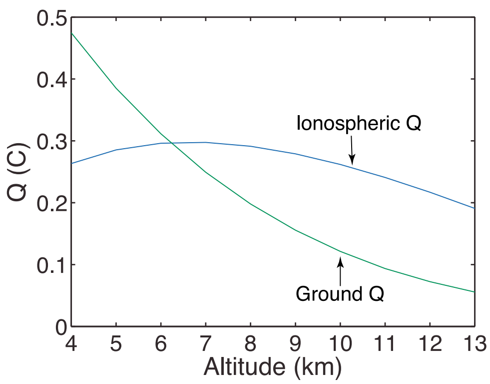

Figure 10. Charge transferred to the ground and to the ionosphere at the end of cloud relaxation phase (t = 1250 sec) as a function of the altitude of the remaining positive charge. These charges represent the deposited charges to the ground/ionosphere because of the dissipation of the 1 C of positive charge and the screening charge that is distributed at the boundaries of the thundercloud.

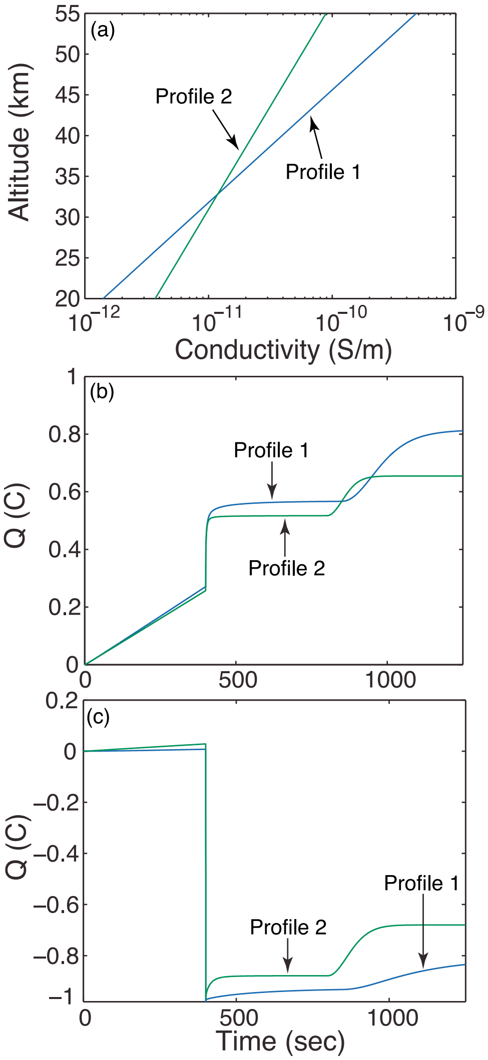

Figure 11. Charge dynamics in the case of a negative CG lightning with $Q_\pm = \pm 1$ C, at altitudes $h_+ = 10$ km and $h_- = 5$ km for two different conductivity profiles. Profile 1 has $\sigma_0 = 5 \times 10^{-14}$ S/m and scale height $l = 6$ km, while Profile 2 has $\sigma_0 = 6 \times 10^{-13}$ S/m and scale height $l = 11$ km. (a) Conductivity profiles as a function of altitude. (b) Charge deposited to the upper boundary as a function of time. (c) Charge deposited to the lower boundary as a function of time.

40 km) and for profile 2 this altitude is at ~55 km (the upper boundary of the simulation domain is set at 55 km).

5. Discussion

5.1. Comparison With Equivalent Model

[49] In Figure 2c we demonstrated that for the case of a single thunderstorm with a single CG lightning discharge the total efficiency is 0.81 (if the CG lightning discharge removes all the accumulated negative source charge). In Figure 5c it has been shown that for the case of single thunderstorm with a single IC lightning discharge the total efficiency is 0 (if the IC lightning discharge neutralizes all the accumulated source charge). From these figures we can see that each of the three phases of the thunderstorm contribute to the total efficiency of the thunderstorm. Specifically, in Figure 2c we can see that from the total 0.81 C that eventually are transferred to the ionosphere, 0.27 C are transferred during the thunderstorm electrification phase (this is transfer due to classic Wilson current), 0.28 C are transferred during the relaxation phase after the removal of −1 C due to the CG lightning discharge, and 0.26 C are transferred during the cloud relaxation phase at the end of the thunderstorm. Based on this, we can define partial efficiency for each of the phases of the thunderstorm. For the electrification phase, the partial efficiency is 0.27, for the relaxation phase it is 0.28, and finally for the cloud dissipation phase the partial efficiency is 0.26. Moreover, since a part of the accumulated charge is removed due to the lightning and the remaining charge will be neutralized during the cloud dissipation phase, we can say that for 1 C that is accumulated in the thundercloud 0.27 C are transferred to the ionosphere during the charging phase, and 0.54 C will be transferred to the ionosphere during the transient phase after the lightning and during the cloud dissipation phase. Therefore for the CG lightning case the phase that creates charge inside the thundercloud has efficiency 0.27 and the phases that remove/neutralize the created charge have efficiency 0.54. The same concept can be applied in Figure 5c for the case of IC lightning discharge.

[50] Figures 2 and 5 indicate that there is a significant difference between the dynamics of the charge flow to the ionosphere and to the ground. Although the absolute value of the total charge that is transferred to these boundaries at the end of the thunderstorm is the same, in agreement with previously discussed ideas of *Mareev et al.* [2008], during each of the phases there is a difference in the time dynamics of the charge transfer. This can be seen clearly in Figure 5c. During the electrification phase, there is charge transfer to the ionosphere but not to the ground. The CG lightning discharge transfers directly 1 C of negative charge to the ground, but nothing to the ionosphere. During the relaxation phase after the lightning there is an amount of charge that is transferred to the ionosphere but a very small amount of charge that is transferred to the ground. Finally during the cloud relaxation phase, there is an additional charge that is transferred to the ionosphere and a significant amount of charge compared to the other slow transient phases that is transferred to the ground. The charge is transferred to the ionosphere only during slow transients before and after the occurrence of the lightning discharge, but charge is transferred to the ground mainly during fast transients (lightning discharge) and slow transients during the relaxation phase at the end of the thunderstorm. We emphasize that the observed effects are significantly dependent on the conductivity distribution in the vicinity of the thundercloud and will be analyzed in future publications.

[51] In *Pasko et al.* [1997] it was shown that in order to study the short term effects (order of milliseconds) caused by a lightning on the ionosphere, we can consider the charge removal as the "placement" of an identical charge of opposite sign. The field above the cloud will be the free space field due to the "newly placed" charge and its image in the ground, which is assumed to be perfectly conducting. The same assumption was used in *Mareev et al.* [2008] for the calculation of the charges that are transferred to the ionosphere and to the ground due to slow transients after an

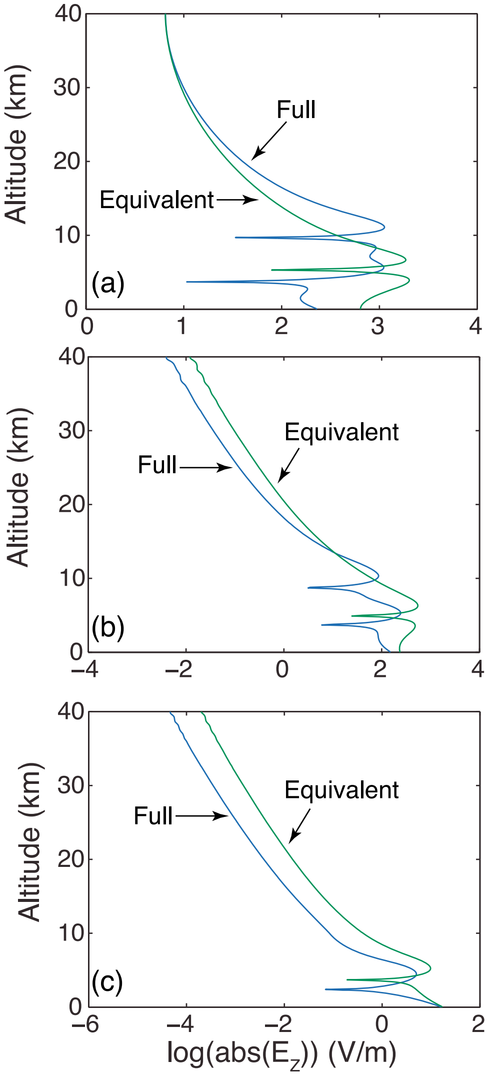

Figure 12. Electric field after a negative CG as a function of altitude at time (a) 1 sec, (b) 100 sec, (c) 450 sec after the removal of −1 C from the system. The electric field is calculated by two methods. The first method takes into account the slow deposition of the charge in the conducting medium and then the removal of −1 C (i.e., the Full model) and the second deposits directly +1 C in a conducting medium at the same altitude as the negative charge in the first method (i.e., the Equivalent model).

occurrence of a lightning. In Figure 12 we present the altitude scan of the electric field at the axis of simulation domain at several time instances after a negative CG, calculated using two methods. In the first method, we take into account the slow deposition of negative and positive charges in a conducting medium (we neglect the term II in (4)) and then we remove −1 C from the system. The second method corresponds to deposition of +1 C at the altitude of the negative charge in the first method.

[52] From Figure 12a, which shows the electric field 1 sec after the CG lightning, it is clear that at the ionospheric altitudes the electric field calculated by these two methods is the same. This justifies the assumption of *Pasko et al.* [1997]. On the other hand, the electric field at lower altitudes is completely different and thus the currents flowing in the conducting atmosphere at lower altitudes are different. As time evolves, we see that the electric fields for the two methods also significantly deviate from each other at higher altitudes (Figures 12b and 12c). These observations lead us to the conclusion that the "equivalent model" is not an accurate and valid model for the study of the currents that flow to the ionosphere and to the ground due to slow transients after the lightning, because it fails to describe accurately the actual charge dynamics at all altitudes in the conducting atmosphere.

[53] The fact that the equivalent model fails to describe accurately the charge dynamics leads to important implications in the context of global electric circuit calculations. In particular, comparison between Figures 2c and 3b reveals the following differences. According to the equivalent model (Figure 3b), the CG lightning results in a deposition of additional positive charge to the upper boundary, which is equal to 0.55 C and to the lower boundary which is equal to ~0.45 C. According to full model (Figure 2c) there is a charging of the system during the charge accumulation stage by deposition of positive charge to the upper boundary and then there is a further charging of the system because of the deposition of additional positive charge as an effect of the lightning and the dissipation of the cloud. The total amount of the charge that is deposited to the upper boundary after the lightning is the same in both models but the contribution of the post-lightning stage to the ground charge appears to be much higher in the equivalent model. This difference comes from the fact that in a realistic thunderstorm the amount of charge that is transferred to the ground after the lightning is dependent on the charging phase of the thunderstorm. Specifically, the ~+0.27 C transferred to the ionosphere and the 0 C transferred to the ground during the charging phase (Figure 2c) led to an effective −0.27 C of charge remaining in the atmosphere before the lightning. These −0.27 C effectively neutralized +0.27 C of charge in the atmosphere that represent the difference between the equivalent model ~+0.45 C (Figure 3b) and the full model ~+0.18 C (Figure 2c) charge amounts deposited to the ground after the lightning. We emphasize that the full model allows us to distinguish each phase of the thunderstorm, to identify the difference in charge flow to the ionosphere and to the ground during the several phases of the thunderstorm, and to quantify the significance and the contribution of each phase, which is not possible by using the equivalent model.

[54] Additionally, comparison between Figures 5c and 6b reveals the following differences. According to the equivalent model (Figure 6b), the IC lightning discharges the GEC because it results a deposition of an equal but opposite amount of charge ~0.23 C to the upper (negative charge is deposited) and lower (positive charge is deposited) boundaries. According to full model calculations (Figure 5c), the pre-lightning phase causes charging of the system, because there is a deposition of positive charge to the upper boundary. The IC lightning discharges the system because it causes a deposition of negative charge to the upper boundary which neutralizes the originally deposited positive charge.

[55] Additional factor that we should take under consideration is that the atmosphere is a conducting medium. If we consider the charge accumulation directly in the atmosphere then because of its conductivity, free charge will be induced

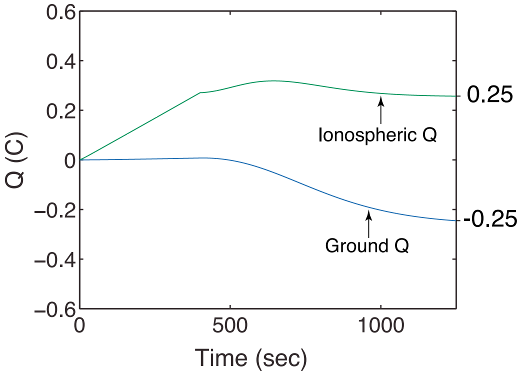

Figure 13. Charge transferred to the ground and to the ionosphere for the case of an electrified cloud that does not produce lightning (see text for details).

which will screen the accumulating charge. This means that it will be very difficult to achieve a sufficient accumulation of charge that will lead to conventional breakdown and thus the occurrence of lightning. In reality, the charge accumulation takes place inside the thundercloud, which according to *Brown et al.* [1971], *Pruppacher and Klett* [1997], and *Rakov and Uman* [2003] has a lower conductivity compared to that of the surrounding dry clean air, due to ion attachment to hydrometeors. These conditions prevent induced free charges from entering the thundercloud and thus the accumulation of charge more readily leads to conventional breakdown inside the thundercloud. This is the reason why term II in (4) is necessary for the correct representation and study of the slow transients especially during the pre-lightning phase.

5.2. Dependence on Charging Time of the Thunderstorm

[56] Another factor that has impact to our calculations is the time duration of each phase of the thunderstorm. In our calculations each phase lasts 400–450 s. In *Mason* [1953] it was assumed that the electrification process before the first lightning discharge occurs lasts approximately 12–20 min. After the first lightning, the electrification process between the flashes of a thunderstorm lasts several seconds [e.g., *Krider and Blakeslee*, 1985]. The cloud top in our model is assumed to be at the altitude of 20 km, where the atmosphere has a relaxation time equal to ~6.3 sec according to the chosen conductivity profile. Moreover, we have seen from Figures 1, 2, 4, and 5 that the most significant amount of charge is induced at the upper boundary of the thundercloud. This means that as long as the charging time is greater than approximately three times the relaxation time of the atmosphere at the cloud top, the charge that is transferred to the ionosphere is quite accurately calculated (the relative difference becomes less than 7%). For different timescales, the slope of the graphs describing initial charging in Figures 2b, 2c, 5b, and 5c will be different for the first 400 sec, but at the end the electrification phase ($t = 400$ sec), the accumulation of 1 C of positive charge and 1 C of negative charge will result the deposition of the same ~0.27 C to the ionosphere (for altitudes of 5 and 10 km of the negative and positive charge, respectively). The relaxation process after the lightning discharge is relatively short. As it can be seen from Figure 2c, during the first 3–5 s after the CG lightning occurs, the charge that is transferred to the ionosphere has already converged to its final value. Assuming that the cloud relaxation process lasts several minutes too, similarly to the electrification phase, we conclude that our results are accurate and allow to follow all the fast and slow transients that occur in the system.

5.3. Positive CG Lightning Case

[57] The linearity of the problem allows us to make conclusions for the case of a positive CG lightning discharge, by inverting the polarities of the charges of the negative model CG discharge case. By placing 1 C of negative charge at 10 km altitude and 1 C of positive charge at 5 km altitude, during the pre-lightning phase positive charge will be distributed around the thundercloud and negative charge equal to −0.27 C will be transferred to the ionosphere. The removal of the positive charge from the thundercloud will lead to an excess of negative charge and thus positive charge will be induced which eventually will be distributed around the thundercloud and negative charge equal to −0.28 C will be transferred to the ionosphere. Although the efficiency will be the same as for the case of the negative CG lightning discharge, the negative charge that is transferred to the ionosphere causes the discharge of the GEC [*Mareev et al.*, 2008; *Rycroft et al.*, 2007].

5.4. Electrified Clouds

[58] The model presented in this paper can be used to estimate the charge that is transferred to the ionosphere and to the ground for electrified clouds that do not produce lightning. To illustrate this case we charge the system for a time interval equal to 400 sec with 1 C positive (at 10 km) and 1 C negative (at 5 km) charge and then we let the system relax by increasing linearly in time the conductivity inside the thundercloud up to the value of conductivity in the surrounding atmosphere (Figure 13). We notice for this case that the GEC at the end of the process is charged with charge equal to 0.25 C. We also note that this amount of charge is transferred to the ionosphere mainly during the electrification of the cloud, and to the ground mainly during the dissipation phase of the electrified cloud. We note that in the quantitative context of the modeling conducted in this paper the contribution of a single electrified cloud to the global electric circuit is ~3 times less than the contribution of a single thunderstorm that produces a negative CG lightning (assuming that both systems possess charges at the same altitudes and with the same values).

5.5. Comparison With Experimental Measurements

[59] Based on their measurements and considering a fair weather conductivity profile determined by *Driscoll et al.* [1992], *Maggio et al.* [2009a] used a one-dimensional approximation to estimate the transient current, the electric field and finally the amount of charge transferred by the above-cloud transient current. In Table 1, the charging phase, lightning transient phase, cloud relaxation phase and total efficiencies are shown, as calculated by our model, for one of the CG and one of the IC flashes presented by *Maggio et al.* [2009a]. The table also includes inferred altitudes of positive (h_+) and negative (h_-) charges inside the

Table 1. Partial and Total Efficiencies for One of the CG and One of the IC Flashes Presented in *Maggio et al.* [2009a]

Flash Type	h_+ (km)	h_- (km)	Charging	Lightning Transient	Cloud Relaxation	Total Efficiency
CG	6.2	3.2	29%	17%	25%	71%
IC	10	7	16%	−15%	0%	1%

thundercloud. In *Maggio et al.* [2009a] the efficiency for the CG flash was found to be equal to 36% and 25%, while for the IC flash case the efficiency was found equal to 12% and 9%, based on measurements conducted at 4 km and 6 km, respectively, above the upper charge of the thundercloud. Comparing these values with the sum of the values for the lightning transient phase calculated with our model, we see that there is a difference. This difference is due to two factors. The first one is that the conductivity profile used in *Maggio et al.* [2009a] does not include the conductivity difference between the inner thundercloud and the surrounding air, while the conductivity profile in our model does. The second factor is that the one-dimensional approximation does not give accurate results for the estimation of the current and the electric field and thus for the transferred charge at altitudes below 40 km. The electric field consists mainly of the z-component at altitudes above 40 km, but neglecting the horizontal components of the electric field at lower altitudes leads to inaccurate calculations of the charges. This is more clear by observing that the efficiencies calculated in *Maggio et al.* [2009a] are decreasing as the altitude of measurements is increasing. This means that as the altitude of observations increases the horizontal components of the electric field are decreasing and eventually at altitudes where the horizontal components are negligible compared to vertical component, the efficiencies will be comparable to the one calculated with our model.

[60] *Mach et al.* [2009] measured the currents above 830 thunderstorms and considering the altitude of the positive charge at 14 km and the altitude of negative charge at 7 km, found that thunderstorms that do not produce lightning produce an average vertical current equal to 0.3 A and thunderstorms that produce lightning produce an average vertical current equal to 0.8 A. From Figure 7, we see that the charge that is transferred to the ionosphere during the electrification phase of the thunderstorm, depends mainly on the spatial separation of the accumulated charges inside the thundercloud. For distance equal to 7 km between the accumulated charges 0.37 C are transferred to the ionosphere for each 1 C of accumulated charge. A typical charging current that reproduce the average lightning rates of both CG and IC lightning flashes is I = 1.5 A [*Krehbiel et al.*, 2004]. Assuming that the charging current for thunderstorms that produce lightning is the same with the charging current of thunderstorms that do not produce lightning, we see that the Wilson current that flows above the thundercloud with charges at the given altitudes is equal to 0.55 A and is 30% larger than the average current that has been measured for the clouds that do not produce lightning. Using the results of our model for the negative CG lightning case, from Figure 7 we see that for accumulation of 1 C at the given altitudes of positive and negative charges, 0.37 C are transferred to the ionosphere during the charging stage. From Figure 8 we see that the removal of 1 C negative charge from the altitude of 7 km causes 0.38 C to be transferred to the ionosphere. Finally from Figure 10 we can derive that during the dissipation of the cloud 0.13 C are transferred to the ionosphere if the remaining positive charge is at 14 km. So the overall charge that is transferred to the ionosphere is 0.88 C and considering a charging current equal to 1.5 A (which means 1.5 C accumulated charge per second), we can find that for thunderstorms that produce negative CG lightning, a current equal to 1.32 A flows to the ionosphere, which is 38% larger than the average value of 0.81 A that was measured and it is larger that the Wilson current that flows above electrified clouds that do not produce lightning.

[61] If we consider that a thunderstorm produces both IC and CG flashes, then we can redo the above calculations by taking additionally into account the effects of the IC flashes. Based on satellite measurements it has been found that the global rate of lightning discharges is 44 ± 5 discharges per second [*Christian et al.*, 2003]. Having assumed 50 discharges per second and 2000 thunderstorms globally [*Rakov and Uman*, 2003, p. 10], there are 0.025 flashes per second per thunderstorm. According to *Rakov and Uman* [2003, p. 324], approximately 75% are IC flashes and 25% are CG flashes, which lead to 0.019 IC flashes per second and 0.006 CG flashes per second per thunderstorm. Moreover, assuming typical amounts of charge that is neutralized/removed from the thundercloud during IC, and −CG lightning discharges to be 17.6, −7 respectively [*Maggio et al.*, 2009b; *Rycroft et al.*, 2007], we can find that there are 0.04 C that are removed from the thundercloud due to the CG flashes per second and 0.32 C that are neutralized inside the thundercloud due to IC flashes per second. From Figures 8, 9 and 10 and for the given altitudes we find that the partial efficiencies for the CG and IC flashes are 0.51 and 0.38, respectively. So, considering a charging current equal to 1.5 A, we find that the accumulation of 1.5 C per second leads to a transfer of 0.55 C per second to the ionosphere during the electrification phase, 0.02 C per second because of the CG flashes and −0.12 C per second because of the IC flashes. So there is a total upward current equal to 0.45 A which is 50% smaller than the average current of 0.81 that was measured and it is also smaller than the Wilson current that flows above the thunderstorms that do not produce lightning and that was calculated by our model. These differences will change if the charging current is smaller, if the charge positions are at different altitudes than the altitudes that have been assumed and if the removed/neutralized charges due to the CG/IC flashes are different than the typical values.

[62] It is clear from Figures 2 and 4 that the slow transients during the accumulation of the charge in the thundercloud play a significant role in the charge transfer mainly to the ionosphere. Assuming that the positive charge is located at 10 km and the negative at 5 km, then during the accumulation of 1 C positive and 1 C negative charges, 0.27 C will be transferred to the ionosphere. For the case of IC flash, the neutralization of 1 C positive and 1 C negative source

charges leads to a transfer of −0.27 C to the ionosphere which neutralizes the initially deposited positive charge and causes a discharge of the system. This agrees with experimental measurements which indicate that the IC flashes discharge the global electric circuit [*Coleman et al.*, 2003; *Holzworth et al.*, 2005; *Marshall et al.*, 1996; *Mareev et al.*, 2008; *Rycroft et al.*, 2007]. On the other hand, for the case of negative CG flash, the removal of −1 C from the altitude of 5 km, leads to a transfer of 0.55 C additionally to the ionosphere and so the negative CG flashes are charging the global electric circuit [*Mareev et al.*, 2008; *Rycroft et al.*, 2007].

5.6. Application to the GEC

[63] The model results presented in this paper allow us to approximate the contribution of CG and IC lightning discharges to the global electric circuit. Based on satellite measurements it has been found that the global rate of lightning discharges is 44 ± 5 discharges per second [*Christian et al.*, 2003]. According to *Rakov and Uman* [2003, p. 324], approximately 75% are IC flashes and 25% are CG flashes. Having assumed 50 discharges per second there are 38 IC and 12 CG flashes. Considering that 90% of the thunderstorms have normal polarity and 10% inverted polarity [e.g., *Rycroft et al.*, 2007], we get 34 normal polarity IC flashes, 4 inverted polarity IC flashes, 11 −CG flashes and 1 +CG flash. Typical altitudes of the lower and upper charges inside the thundercloud that lead to IC and CG flashes are 7 km and 10 km respectively and a typical charging current that reproduce the average lightning rates of both CG and IC lightning flashes is $I = 1.5$ A [*Krehbiel et al.*, 2004]. Moreover typical amounts of charge that is neutralized/removed from the thundercloud during IC, −CG, +CG lightning discharges are 17.6, −7, 40 C respectively [*Maggio et al.*, 2009b; *Price et al.*, 1997; *Rycroft et al.*, 2007]. The partial efficiency of the cloud electrification phase depends on the distance between the accumulated charges. From Figure 7 we can deduce that for distance equal to 3 km the efficiency is 0.14. This leads to a charging current equal to 0.21 A for a single thunderstorm of normal polarity and a discharging current equal to 0.21 A for a thunderstorm of inverted polarity. Out of 2000 active thunderstorms [*Rakov and Uman*, 2003, p. 10], 1800 are of normal polarity causing a global charging current equal to 387 A (comparable to the current used in *Rycroft and Odzimek* [2010] and *Rycroft et al.* [2007] although these authors assumed 1000 thunderstorms globally) and 200 of them are of inverted polarity that cause a discharge current equal to 43 A.

[64] The partial efficiency for the transient phase after the occurrence of CG lightning depends on the altitude of the removed charge, and from Figure 8 we see that for altitude equal to 7 km the efficiency is 0.38. The partial efficiency for the transient phase after the occurrence of an IC lightning discharge depends on the distance between the neutralized charges. From Figure 9 we can deduce that for distance 3 km, the efficiency is equal to 0.13. So we can derive that for +CG flashes there is a global discharging current equal to 15.2 A, for the −CG flashes there is a global charging current equal to 29.3 A, for IC flashes of normal polarity there is a global discharging current equal to 77.8 A and for IC flashes of inverted polarity there is a global charging current equal to 9.15 A. Finally for the cloud relaxation phase, if the remaining charge is at 10 km, from Figure 10 we can see that the partial efficiency is 0.23. This leads to a charging current equal to 2.53 A for the −CG flashes and a discharging current equal to 0.23 A for the +CG flash.

[65] Having summed all the currents (charging and discharging) we can find that there is a sustaining charging current equal to 292 A that is produced globally by thunderstorms that produce lightning, and which is ∼26.5% of the total sustaining current (which is assumed to be in the order of magnitude of 1 kA [e.g., *Bering et al.*, 1998; *Rycroft et al.*, 2007]). The main part of the global current that is produced by thunderstorms that produce lightning is created during the electrification phase of the thunderstorm. The overall contribution of the CG lightning discharges is a charging current equal to 14.1 A, which is only the 1.28% of the total sustaining current. Thus the CG flashes have a minor contribution to the global electric circuit as it has been shown by previous works [e.g., *Williams*, 1992; *Fullekrug et al.*, 1999; *Williams and Satori*, 2004; *Markson*, 2007; *Rycroft et al.*, 2007]. Moreover, the overall contribution of the IC lightning discharges is a downward net current that discharges the GEC, it is 68.6 A and it is 6.24% of the total sustaining current. The contribution of the IC flashes to the GEC, although it is about 5 times larger than the contribution of the CG flashes, is still small. The larger contribution of the IC flashes, compared to the contribution of the CG flashes, is mainly due to their more frequent occurrence compared to the occurrence CG flashes.

6. Conclusions

[66] The conclusions of the current paper can be summarized as follows:

[67] 1. Based on the model and the data presented, it was shown that the charge accumulation stage should be taken into account for the study of the charge transfer to the ionosphere and to the ground in association with lightning discharges. The amount of induced charge that is transferred to the ionosphere during the charge accumulation phase prior to the lightning is comparable to the charge that is transferred during the slow transients after the lightning occurrence.

[68] 2. In addition to the charge accumulation and the lightning phases, the quantitative description of the thunderstorm dissipation phase is also important for understanding of the overall contribution of the thunderstorms to the GEC.

[69] 3. Numerical simulations reported in the present work demonstrate that the charges that are transferred to the ionosphere and to the ground depend on the atmospheric conductivity profile, on the conductivity distribution within the thundercloud, on the altitudes of the charges that are deposited/removed in/from the thundercloud and on their spatial separation.

[70] 4. For all kind of lightning discharges the time dynamics of the charge flow to the ground are different from the time dynamics of the charge flow to the ionosphere. These dynamics are sensitive to the conductivity distribution in the vicinity of the thundercloud. For the model conductivity distribution studied in the present work, there is a charge flow to the ionosphere during all phases of the thunderstorm evolution, but there is charge flow to the ground

only by the direct deposition of charge during the CG lightning discharge and the cloud dissipation phase.

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