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INTERACTION WITH THE LOWER IONOSPHERE OF ELECTROMAGNETIC PULSES FROM LIGHTNING: HEATING, ATTACHMENT, AND IONIZATION

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Abstract. A Boltzmann formulation of the electron distribution function and Maxwell's equations for the electromagnetic (EM) fields are used to simulate the interaction of lightning radiated EM pulses with the lower ionosphere. Ionization and dissociative attachment induced by the heated electrons cause significant changes in the local electron density (N_e). Due to 'slow' field changes of typical lightning EM pulses over time scales of tens of μs, the distribution function follows the quasi-equilibrium solution of the Boltzmann equation in the altitude range of interest (70 to 100 km). The EM pulse is simulated as a planar 100 μs long single period oscillation of a 10 kHz wave injected at 70 km. Under nighttime conditions, individual pulses of intensity 10-20 V/m (normalized to 100 km horizontal distance) produce changes in N_e of 1-30% while a sequence of pulses leads to strong modification of N_e at altitudes <95 km. The N_e changes produce a 'sharpening' of the lower ionospheric boundary by causing a reduction in electron density at 75-85 km (due to attachment) and a substantial increase at 85-95 km (due to ionization) (e.g., the scale height decreases by a factor of ~2 at ~85 km for a single 20 V/m EM pulse). No substantial N_e changes occur during daytime.

1. Introduction

'Early' subionospheric VLF perturbations occurring within 20 ms of causative lightning have been interpreted to be due to substantial heating and ionization of the lower ionosphere by lightning EM radiation [*Inan et al.*, 1991; hereafter refered to as I], also consistent with observations from the space shuttle [*Boeck et al.*, 1992; *Taranenko et al.*, 1992] of transient airglow brightening over a thunderstorm center.

EM pulses from lightning have typical durations of ~50-150 μs and peak electric field amplitudes up to 50 V/m [*Uman*, 1987] at horizontal distances of 100 km from the flash. Electric fields >16 V/m would cause avalanche ionization of neutrals in the ionosphere at 100 km altitude, where the electron mean free path is about a meter. However, since the EM pulse would be attenuated during the acceleration process at lower altitudes, a self consistent formulation is needed which properly accounts for the energy losses, the evolution of the electron distribution function, and the space-time evolution of the EM pulse. In this paper we introduce a self consistent time domain solution of the Boltzmann equation for the electrons and the one dimensional Maxwell's equations for the fields.

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2. Formulation of the Problem

We use the U.S. Standard Atmosphere [1976] for the ambient neutrals (Fig. 1) at altitudes (h) of 70 to 100 km with 80% molecular nitrogen (N_2) and 20% molecular oxygen (O_2). Our results are only weakly dependent on the ambient neutral temperature (T), taken to be 250° K throughout the region. We consider ambient N_e profiles representing 'nighttime' (a), 'daytime' (c), and intermediate (b) cases (Fig. 1).

We assume the ambient magnetic field lies in the horizontal plane and the incident EM wave is planar, with the wave electric field $\vec{E}$ either *i)* parallel to $\vec{B}_0$, or *ii)* perpendicular to $\vec{B}_0$. Although this configuration is most directly applicable to interactions near the geomagnetic equator, the plasma is collision dominated so that the orientation of $\vec{B}_0$ plays a minor role in the coupling process.

We express the electron distribution function as [*Allis*, 1956]

$$f(\vec{r},\vec{v},t) = f_0(\vec{r},v,t) + \frac{\vec{v}\cdot\vec{f}_1(\vec{r},v,t)}{v} + \ldots \quad (1)$$

assuming that the random electron velocity is much larger than its average directional velocity and expanding $f(\vec{r},\vec{v},t)$ in spherical functions of zero order. For a weakly ionized plasma, the Boltzmann equation for $f(\vec{r},\vec{v},t)$ can be expressed as [*Gurevich*, 1978]

$$\frac{\partial f_0}{\partial t} = \frac{e}{3mv^2}\frac{\partial}{\partial v}\left(v^2\vec{E}\cdot\vec{f}_1\right) + \frac{1}{2v^2}\frac{\partial}{\partial v}\left(v^2\delta\nu_{el}(v)[\frac{T}{m}\frac{\partial f_0}{\partial v} + v f_0]\right) + S_{0in} \quad (2a)$$

$$\frac{\partial \vec{f}_1}{\partial t} = \frac{e\vec{E}}{m}\frac{\partial f_0}{\partial v} + \frac{e}{mc}[\vec{B}_0\times\vec{f}_1] - \nu(v)\vec{f}_1 \quad (2b)$$

$$S_{0in} = S_{0in}^{rot} + S_{0in}^{vib} + S_{0in}^{opt} + S_{0in}^{dis} + S_{0in}^{att} + S_{0in}^{ion} \quad (3)$$

where m is the electron mass, and $\nu(v)$ is the total collision frequency, δ is the fraction of electron energy lost per collision, and $\nu_{el}(v)$ is the elastic collision frequency. S_{0in} concerns inelastic collisions consisting of rotational, vibrational, optical, dissociative, dissociative with attachment, and ionizational losses [*Gurevich* 1978]. The dissociative attachment of electrons and ionization are processes that affect the electron density. We neglect existing spatial gradients of $f(\vec{r},\vec{v},t)$. Cross sections σ_j^α are taken from *Murphy* [1988].

We solve equations (2) using a numerical technique described by *Rockwood and Greene* [1980], which conserves energy and the number of particles. The time evolution of $f(\vec{r},\vec{v},t)$ in a single slab located at h = 90 km for E = 10 V/m applied for 20 μs starting at t = 0 is shown in Fig. 2 (a). The distribution function is initially a Maxwellian with a

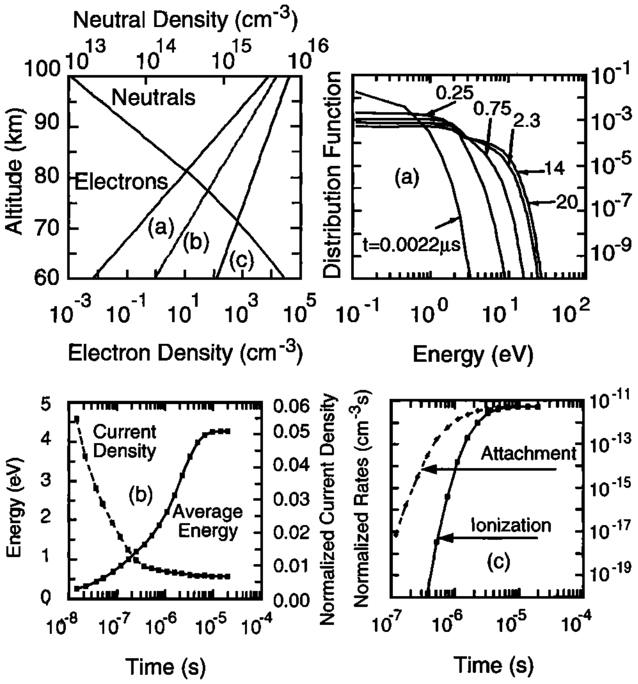


Fig. 1. (Top left) Ambient profiles of electron and neutral densities. Electron density profile (a) is for nighttime, profile (c) is for daytime, and profile (b) represents intermediate. Fig. 2. Time evolution at h = 90 km of (a) (top right) the electron distribution function, (b) (bottom left) the normalized electric current and average electron energy, and (c) (bottom right) the attachment and ionization rates.

temperature of $\sim$250° K. After the onset of the E field, the average energy of the electrons (Fig. 2b) increases, reaching a constant value of $\sim$4.3 eV in 10 μs at which time $f(\vec{r}, \vec{v}, t)$ has reached its equilibrium state, characterized by an almost flat distribution below $\sim$1.5 eV with a drop between 1.5 and 3 eV due to the vibrational barrier of N_2, and a second flat region from 3 to 6 eV due to a gap in the electron loss function [*Tsang et al.,* 1991], followed by a precipitous drop as electrons reach energies above the major electronic thresholds of the constituents. The time evolution of the ionization and attachment rates are shown in Fig. 2 (c).

Since lightning radiated EM fields exhibit relatively slow time variations over 10 μs scales (e.g., [*Brook et al.,* 1989]), with pulse durations of typically 50-150 μs, the current density and the ionization and attachment rates can be approximated by their steady state values derived for a given $\vec{E}$ existing at a particular time, at the given h. A table of equilibrium values of current density (J) and electron density (N_e) variation rates as a function of h and E were prepared, covering the 70-100 km range in 1 km increments and the E range in 50 points. The maximum value of E over the grid is 70 V/m below h = 80 km and is gradually reduced to 3 V/m at 100 km. For h > 100 km the medium is approximated by its characteristics at 100 km. Maxwell's equations were then solved in a self consistent manner by using linear interpolation on this grid.

The E, J, and N_e values were monitored at fixed h as the EM pulse propagated through and checked against single slab results. Fig. 3 (a) shows $E(t)$ at 89 km calculated using the grid values for a 20 V/m and 100 μs sinusoidal pulse injected at 70 km for profile (a) of Fig. 1. Fig. 3 (b) shows J as obtained from the corresponding grid values and Fig. 3 (d) shows J as computed by a time dependent solution of (2) for a single slab at this altitude and for the $E(t)$ of Fig. 3 (a). The difference between the two is barely visible on the scale shown, which validates our use of the equilibrium solutions. The difference between N_e values calculated using the equilibrium and the single-slab time dependent solutions is $\sim$3.5% (Fig. 3c). Overall, the error introduced in our results due to the usage of the quasi-equilibrium solution is <10%.

3. Results

We inject at h = 70 km a 100 μs long EM pulse represented by a single 10 kHz cycle with amplitude E_{70} and with $\vec{E}$ parallel to $\vec{B}_o$. We solve Maxwell's equations to simulate the propagation of the pulse and equations (2) to describe its evolution as it interacts with the ionosphere for $\sim$260 μs. We maintain zero field boundary conditions at the upper boundary (120 km) consistent with strong attenuation and reflection in the lower layers. Leaving aside directional aspects of the radiation from cloud-to-ground versus intracloud discharges, E_{70} = 20 V/m corresponds to E_{100} $\sim$14 V/m at 100 km distance. According to *Krider and Guo* [1983], the mean amplitude for cloud-to-ground discharges is 5 V/m, with E_{100} > 20 V/m occuring $\sim$10% of the time.

Often the time interval between consecutive discharges from thunderstorm cells is less than a second [*Uman,* 1987, p. 19], which is much less than the relaxation time (10 to 100 s) of the density perturbations in the D-region. In such cases, the ionization produced by consecutive strokes would accumulate [I]. In modeling this accumulation we neglect relaxation during the time between strokes and supply incident EM energy for $\sim$2.2 ms, a time that corresponds to $\sim$20 consecutive lightning strokes.

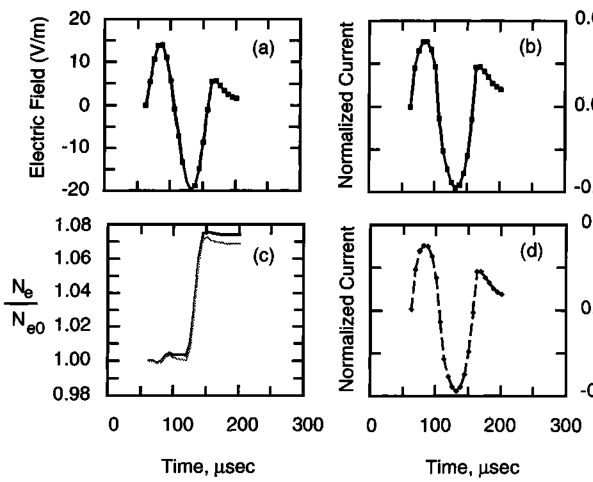


Fig. 3. Variations with time of the electric field (a) and the electric current density (b) at h = 89 km for nighttime conditions following the injection of a 20 V/m EM pulse starting at t = 0 at 70 km. Single slab calculations of the electric current for the electric field varying as in (a) at 89 km are also shown in (d). Plot (c) shows comparison of the electron density changes as calculated from the grid model and from the single slab calculations at 89 km for the electric field varying as in (a).

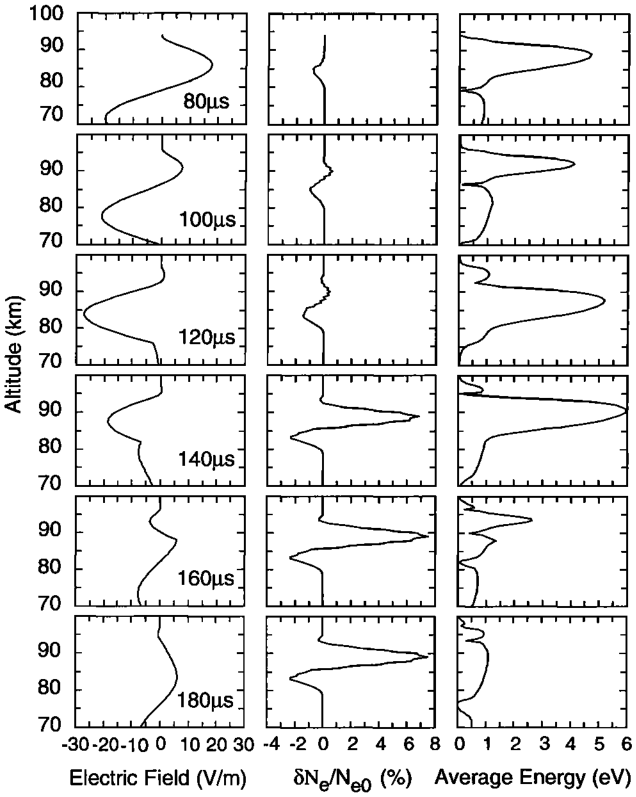
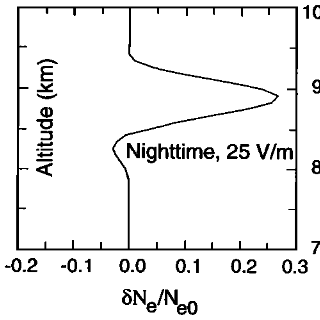


Fig. 4. Snapshots of the electric field, normalized electron density change ($\delta N_e/N_{eo}$), and average electron energy covering the 80 to 180 μs time interval in 20 μs increments following the injection of a 20 V/m EM pulse at 70 km under nighttime conditions.

3.1 Nighttime Ambient Conditions

Time evolution of the interaction is shown in Fig. 4 for the ambient density profile of Fig. 1(a). As the wave propagates upward it becomes progressively attenuated and is partially reflected. At 80 μs, with the wave front at 94 km, the amplitude at h = 85 km has decreased to ~17.5 V/m. However, E exceeds the input intensity (20 V/m in this case) as a result of constructive interference, as seen at 120 μs, when $E \simeq 27$ V/m at ~83 km. Lightning EM fields penetrating above 97 km are strongly attenuated. The average electron energy at times exceeds 5 eV, providing a substantial number of electrons with energy higher than the thresholds for dissociative attachment (~6 eV) and ionization (~16 eV) and thus leading to changes in N_e. At 79 - 86 km and at 92 - 95 km dissociative attachment prevails, causing decreases in N_e. In the center of the interaction region, 86 - 92 km, N_e is increased as ionization dominates. The major increase in N_e occurs at the time of constructive interference of the downgoing reflected first half of the pulse with the upgoing second half, with maximum resulting $|\delta N_e/N_{eo}|$ of ~-3% at 83 km and >+7% at 89 km. For 18 successive EM pulses with E_{70} = 20 V/m the density changes built up to a depletion of ~48% at 83 km and a density increase of >150% at 89 km.

A pulse with 100 μs duration but with E_{70} = 10 V/m causes only a weak (<1%) N_e decrease at 87 km, whereas a ~20% N_e decrease occurs for 20 successive EM pulses of this strength.



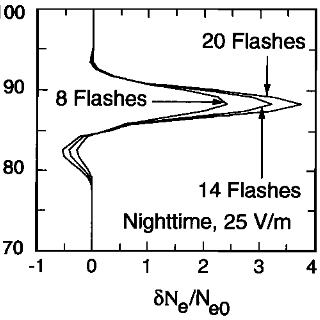


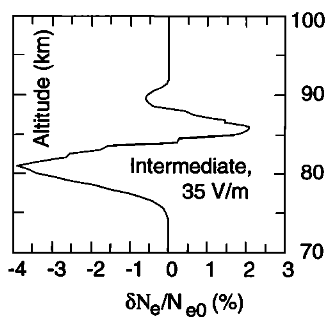
Fig. 5. (Left) The resulting density changes for a single EM pulse with E_{70} = 25 V/m initial amplitude. Fig. 6. (Right) The resulting density changes for 8, 14, and 20 successive EM pulses with 25 V/m initial amplitude. Both for the nighttime conditions.

A single 100 μs pulse with E_{70} = 25 V/m causes up to a 27% increase at ~89 km and a decrease of ~4% at ~83 km as shown in Fig. 5. The resulting N_e changes for 8, 14, and 20 successive lightning strokes with E_{70} = 25 V/m are shown in Fig. 6. The depletion reaches to ~55% of the ambient at ~83 km, and the N_e increase is >350% at 89 km. The drastic differences between the results for E_{70} of 10, 20, and 25 V/m underscores the highly nonlinear nature of the interaction.

For the intermediate ambient N_e profile of Fig 1(b) and for E_{70} = 35 V/m the N_e changes are shown in Fig. 7 and 8. For pulses with E_{70} <30 V/m, $|\delta N_e/N_{eo}|$ is single peaked and purely negative at ~83 km.

3.2 Daytime Conditions

For the daytime profile of Fig. 1(c), similar calculations indicate that even for the strongest pulses (E_{70} = 50 V/m) $|\delta N_e/N_e| \leq 3 \times 10^{-3}$ per pulse with a maximum at ~76 km. Such perturbations are unlikely to be detectable or significant in terms of overall lower ionospheric dynamics. Hence, during daytime most of the EM energy goes into the excitation of the molecular levels lower than those of ionization and dissociative attachment.



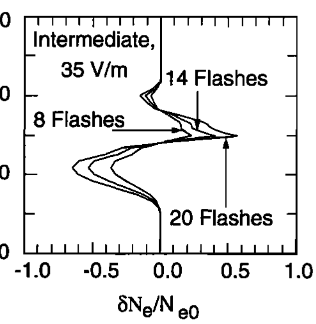


Fig. 7. (Left) The resulting density changes for a single EM pulse with E_{70} = 35 V/m initial amplitude. Fig. 8. (Right) The resulting density changes for 8, 14, and 20 successive EM pulses with 25 V/m initial amplitude. Both for the intermediate conditions.

3.3 Dependence on Orientation of the Electric Field

Similar calculations for the case of $\vec{E} \perp \vec{B}_0$, indicates that for the same E amplitudes and pulse duration, the maximum *positive* N_e perturbations are 15 to 30% smaller and are at 2 to 3 km higher than for the case of $\vec{E} \parallel \vec{B}_0$. For E_{70} = 20 V/m, a 100 μs pulse with perpendicular orientation for nighttime conditions produces ~6% density increase at ~91 km in comparison to >7% increase at 89 km for the parallel orientation (see Fig. 4).

These differences arise from the fact that above a certain altitude (depending on electron energy) the effect of $\vec{B}_0$ on the electron perpendicular motion is not negligible and that for $\vec{E} \perp \vec{B}_0$, the electric current generated by a wave of the same strength is smaller than that for $\vec{E} \parallel \vec{B}_o$.

4. Summary and Discussion

Our results indicate that EM radiation originating in lightning discharges causes substantial changes in ionization in the nighttime lower ionosphere. The changes in N_e produced by individual strokes of initial amplitude E_{100} = 7 to 18 V/m are in the range of 1-30% while a typical sequence of subsequent strokes can lead to > 300% modification of N_e at $h < 95$ km. The density changes produced by lightning EM radiation lead to a 'sharpening' of the lower ionospheric boundary by causing a reduction in N_e at $h = 75 - 85$ km and a substantial increase at $h = 85 - 95$ km. This sharpening may be characterized by a decrease in scale height of a factor of 2 over $83 \leq h \leq 90$ km for a E_{100} = 20 V/m discharge.

Our model accounts for all important aspects of the electrodynamic coupling of an intense EM pulse to a collisional plasma, including a variety of loss processes, the evolution of $f(\vec{r}, \vec{v}, t)$ in the presence of the wave field and the space-time evolution of the EM pulse as it propagates upward and exchanges energy with the electron gas. The main limitations of our model are (*i*) that we consider the one dimensional problem with a horizontal magnetic field (this does not mask any fundamental aspect of the electrodynamic coupling since the plasma is collsion dominated) and (*ii*) that we adopt a quasi-equilibrium solution of (2) in recognition of the relatively 'slow' field changes characteristic of EM pulses from lightning.

The predicted modifications in N_e of 5-30% for single flashes are sufficient to produce detectable amplitude and phase changes in subionospheric VLF signals. In this sense, our results reaffirm the conclusions of [I].

An important prediction of [I] was the possible formation of ionization bubbles over thunderstorm centers due to the accumulation of ionization produced by successive strokes. Our complete analysis shows that this is indeed the case, with the added caveat that the density is depleted at lower altitudes and that the density profile is substantially sharpened as the 'bubble' builds up.

Changes-in lower ionospheric density modify the natural conductivity and therefore ULF waves range can be generated, as possibly evidenced by recent observations [*Fraser-Smith*, 1993] of increased ULF activity near thunderstorms.

We note that the significantly elevated electron temperatures would also lead to the excitation of a variety of optical emissions [*Taranenko et al.,* 1992]. The heated electrons also provide an energy reservoir that can possibly stimulate a number of chemical reactions in the upper atmosphere and alter the aeronomical equilibrium in that region.

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