D REGION DISTURBANCES CAUSED BY ELECTROMAGNETIC PULSES FROM LIGHTNING

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Abstract. Electromagnetic pulses from weak lightning discharges (E_{100} = 1 V/m, where E_{100} is the field strength in the radiation pattern maximum at 100 km) may substantially heat D region electrons, while only pulses with $E_{100} \geq$ 20 V/m may create electron density enhancements $\geq$10 % of ambient. A E_{100} = 20 V/m pulse from a horizontal radiator at 5 km altitude (e.g., the cloud discharge at the stepped-leader onset) increases the electron temperature by a factor of ~400 maximum and the electron density (in one ionization cycle) by ~230 cm^{-3} maximum; the widths at half-maximum of the heated and ionized regions are 200 km and 90 km. A E_{100} = 40 V/m pulse from a vertical radiator at 0 km altitude (e.g., the vertical return stroke channel) increases the electron temperature by a factor of ~350 maximum and the electron density (in one ionization cycle) by ~80 cm^{-3} maximum; the widths at half-maximum of the heated and ionized regions are 440 km and 260 km. Several ionization cycles should occur during a typical lightning pulse.

1. Introduction

Electromagnetic (EM) pulses radiated by lightning discharges may cause heating, optical emissions, and secondary ionization in the nighttime D region [*Inan et al.*, 1991; *Taranenko et al.*, 1992]. Possible evidence includes a transient brightening in the airglow above a lightning flash observed from the Space Shuttle [*Boeck et al.*, 1992], and perturbations of subionospheric very-low-frequency (VLF, 3-30 kHz) signals lasting 10-100 s, attributed to secondary ionization near the VLF reflection height in the Earth-ionosphere waveguide, with onsets within <20 ms of lightning [*Inan et al.*, 1988]. In this paper, we use the model of *Inan et al.* [1991] to investigate the effect of radiated electric (E) field strength and discharge orientation on the magnitude and structure of heating and secondary ionization in the D region.

We range-normalize peak radiated E-fields to E_{100}, the free-space field 100 km from the discharge in the direction of the radiation pattern maximum [*Orville et al.*, 1987]. In two case studies, the percentages of first-return-stroke E_{100} greater than 10 and 20 V/m were 40% and 10% [*Krider and Guo*, 1983]. An E_{100} of 46 V/m from a positive return stroke has been measured [*Brook et al.*, 1989]. The mean first-zero-crossing time of the bipolar waveform from negative summer return strokes in one study was 79 μs [*Ishii and Hojo*, 1989]. We model the return stroke as a vertical infinitesimal dipole at the Earth's surface [*Krider and Guo*, 1983] radiating pulses with E_{100} = 10, 20, and 40 V/m.

A cloud discharge may have a significant horizontal component [*Boeck et al.*, 1992] that illuminates the ionosphere directly overhead. We take as examples of cloud discharges the pulses observed at the onset of the stepped leader in cloud-to ground (CG) flashes, which originate at 4-6 km altitude [*Beasley et al.*, 1982] and which sometimes have peak field strengths (measured on the ground) comparable to those from associated return strokes [*Weidman and Krider*, 1979; *Brook*, 1992] and first-zero-crossing times of ~20 μs [*Weidman and Krider*, 1979]. We model a horizontal cloud discharge as an infinitesimal dipole 5 km above the Earth's surface radiating a E_{100} = 20 V/m pulse, in comparison with a E_{100} = 40 V/m vertical return stroke channel since observed peak fields from stepped-leader onsets tend to be somewhat less than those from the following return strokes [*Brook*, 1992]. The maximum field radiated by some horizontal cloud discharges may exceed the observed values since the ground-based measurements may be close to the null of the radiation pattern.

2. Description of the Heating and Ionization Model

The power U_p dissipated in a unit volume by one magnetoionic component (ordinary or extraordinary) of the EM pulse is $U_p = 2\omega\chi P_d/c$, where ω is the angular wave frequency, χ is the imaginary part of the refractive index of the magnetized, weakly-ionized D region plasma, P_d is the Poynting flux of the component, and c is the speed of light in vacuum. The balance between the energy gained by the electron from the EM pulse and the energy lost in collisions with neutrals is $dQ/dt + G\nu(Q - Q_o) = U_p/N_e$, where Q is the average electron kinetic energy, Q_o is its ambient value, $G = 1.3 \times 10^{-3}$ is the fraction of an electron's energy lost in one collision, N_e is the ambient electron number density, and ν is the effective electron-neutral collision frequency ($\nu \sim Q \sim T_e$) [*Inan et al.*, 1991, and references therein]. Then, for a given U_p,

$$\Delta\nu(t) = \nu - \nu_o = \left(\frac{\gamma}{2G} - \frac{\nu_o}{2}\right)\left(\frac{1 - e^{-\gamma t}}{1 + \epsilon e^{-\gamma t}}\right) \qquad (1)$$

where $\gamma = \sqrt{8G\nu_o U_p(3kN_e T_{eo})^{-1} + G^2\nu_o^2}$, ν_o is the ambient collision frequency, k is Boltzmann's constant, T_{eo} = 300 K, and $\epsilon = (1 - G\nu_o/\gamma)/(1 + G\nu_o/\gamma)$. For cases of moderate to strong heating $\epsilon \simeq 1$, the approximation used by *Inan et al.* [1991]; in the case of weak heating the full expression for ϵ must be used. For typical lightning power levels, γ^{-1} in the peak heating region (90-95 km) is ~10 μs and decreases with decreasing altitude. Equation (1) is evaluated for t=50 μs, which gives $\Delta\nu$ close to steady-state.

At the starting altitude (20 km) P_d is determined from the source location, radiation pattern, and E_{100}. For simplicity we assume no coupling between the two wave components and no refraction or reflection along a given ray originating at the source. P_d is assumed to vary inversely as the square of the distance from the source. Along each ray path, (1) is solved at 0.1 km steps in altitude for each mode, and the results are added to give a total $\Delta\nu$. To account for self-

absorption, the value of ν used to calculate χ (and hence U_p and $\Delta\nu$) at a given altitude is determined by adding ν_o at this altitude to $\Delta\nu$ from the previous altitude. The calculations concern the 5-kHz component of return-stroke pulses and the 30-kHz component of stepped-leader-onset pulses, the respective spectral maxima [*Arnold and Pierce*, 1964]. The choice of ω is relatively unimportant since, for high P_d, $\omega\chi$ and U_p are weakly dependent on ω for $f = \omega/2\pi = 1-100$ kHz [*Inan et al.*, 1991], the portion of the radio spectrum in which return strokes and stepped-leader-onset discharges radiate most intensely [*Arnold and Pierce*, 1964].

The number density of secondary electrons ΔN_e created in a single ionization cycle is estimated by calculating the energy density in the tail of the electron distribution (assumed to be Maxwellian) above 35 eV (the average primary electron energy necessary to ionize N_2 [*Rees*, 1989, p. 40]) and dividing by 35 eV. An ionization cycle is defined as the inverse of the ionization collision frequency $\nu_i = vN_n\sigma_i(v)$, where v is the individual electron velocity, N_n is the number density of neutrals, and $\sigma_i(v)$ is the velocity-dependent ionization cross-section of the neutrals. For a 35-eV electron at 90 km, where $N_{N_2} \simeq 5 \times 10^{13}$ cm^{-3} and $\sigma_i(v) \simeq 10^{-16}$ cm^2 [*Rees*, 1989, pp. 248, 272], the ionization cycle is ~ 0.6 μs. Thus, several ionization cycles occur during one EM pulse.

The ambient collision frequency and electron density profiles used in this paper are plotted in Figure 1 in terms of the magnetoionic quantities $Z_o(h) = \nu_o(h)/\omega$ and $X(h) = \omega_p^2(h)/\omega^2$, respectively, where ω_p is the angular plasma frequency, for $f = 5$ kHz. The $X(h)$ profiles represent a tenuous (a), an average (b), and a relatively dense (c) nighttime D region and an average (d) daytime D region. The lightning is assumed to occur at 50.8°N geomagnetic ($L \simeq 2.5$, magnetic dip angle $= 67.8°$, normalized electron gyrofrequency $Y = \omega_H/\omega \simeq 280$ for $f = 5$ kHz).

3. Results

The T_e and ΔN_e created in a single ionization cycle above a horizontal dipole at 5 km altitude are shown in Figure 2
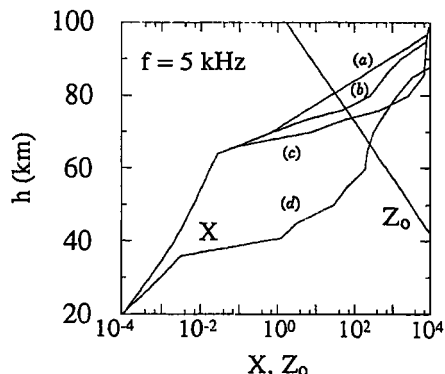

Fig. 1. Ambient collision frequency and electron density profiles expressed as magnetoionic quantities $Z_o(h)$ and $X(h)$ for $f = 5$ kHz. The collision frequency profile was used by *Inan et al.* [1991]. The tenuous nighttime ambient $X(h)$ (a) is similar to that used by *Inan et al.* [1991], the average profile (b) is given by *Reagan et al.* [1981] below 90 km, and the dense profile (c) is ten times (b) at 70-90 km. The International Reference Ionosphere [*Rawer et al.*, 1978] is adopted above (a) 97 km, (b) 90 km, and (c) 95 km. The daytime ambient $X(h)$ (d) is given by *Reagan et al.* [1981].
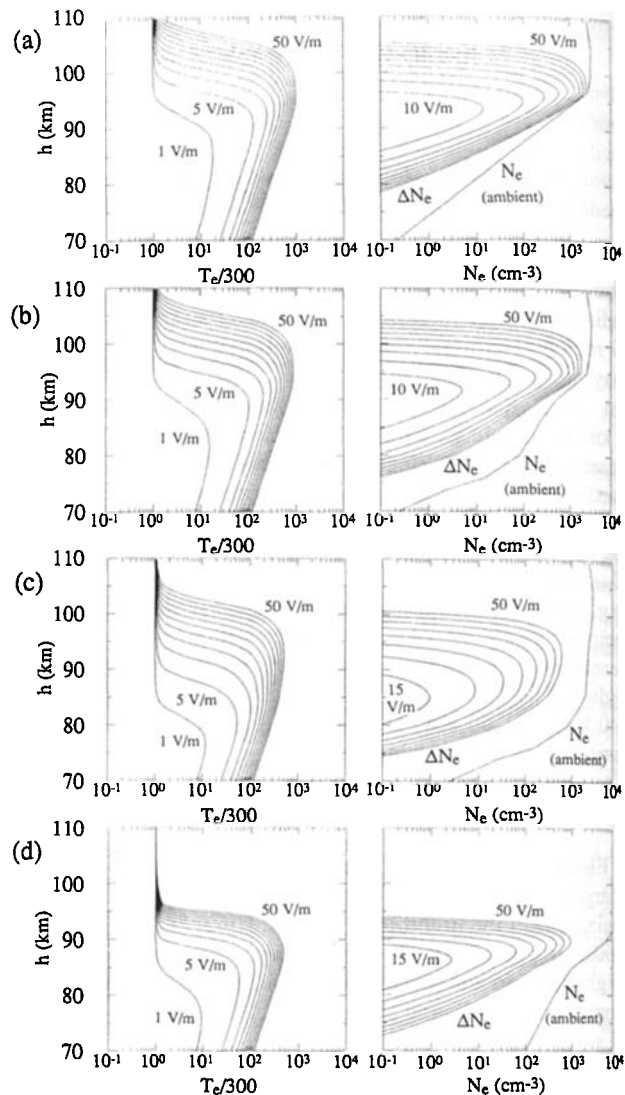

Fig. 2. Heating and ionization of the D region by the EM pulse from a horizontal discharge at 5 km altitude. Electron temperature T_e normalized to 300°K (left), and secondary ionization ΔN_e (right), are shown as functions of altitude parametric in E_{100}, for nighttime electron density profiles a, b, and c, and for daytime profile d. The ambient electron density N_e is also plotted in each case. $E_{100} = 1$ V/m and 5-50 V/m in steps of 5 V/m. All results shown here are for 5 kHz but are similar for 30 kHz. Absorption is found to be nearly independent of frequency for $f = 1$-100 kHz [*Inan et al.*, 1991].

parametric in E_{100} for a tenuous (a), an average (b), and a relatively dense (c) nighttime D region and an average (d) daytime D region. The ambient N_e is also shown. Both T_e and ΔN_e depend nonlinearly on E_{100} at a given altitude. Although relatively weak lightning discharges ($E_{100} = 1$ V/m) heat the D region plasma substantially, only discharges of $E_{100} > 20$ V/m create $\Delta N_e \geq 10\%$ of ambient in a single ionization cycle, due to the minimum electron energy required for impact ionization of N_2. In denser D regions, significant self-absorption of the wave occurs at lower altitudes, resulting in greater ΔN_e at these altitudes.

The transverse extent of the D region disturbance at a given altitude above the lightning discharge is estimated by

calculating T_e and ΔN_e at points along rays spaced in azimuth and elevation angle so as to illuminate points on a two-dimensional horizontal grid at this altitude. The normalized heating $(T_e/300)$ caused by a horizontal discharge at 5 km oriented east-west geomagnetically is shown in Figure 3a over a 500 km x 500 km area centered over the discharge for $E_{100} = 20$ V/m. The heating caused by a vertical discharge at 0 km is shown in Figures 3b, c, and d over the same area for $E_{100} = 10$, 20, and 40 V/m. Each case is plotted at the altitude of maximum heating, which increases with E_{100} for a given discharge type. The heating caused by the horizontal dipole shows a central maximum and a north-south elongation due to the assumed east-west orientation of the discharge (Fig. 3a). The north-south and east-west widths at half the maximum T_e are 200 km and 150 km, respectively. The heating caused by the vertical dipole shows the expected central null (Figs. 3b, c, and d). The width at the outer half-maximum is 410 km for $E_{100} = 10$ and 20 V/m, and 440 km for $E_{100} = 40$ V/m. The cylindrical symmetry in these cases is due to the intense heating $(T_e/300 \gg 1)$, which results in $\nu > \omega_H$ and hence a collision-dominated plasma. In contrast, relatively weak heating by VLF transmitters exhibits a substantial north-south asymmetry in T_e due to the dependence of χ on the wave normal angle [*Inan et al.*, 1992].

The ΔN_e produced in a single ionization cycle is 12% of ambient for a 20 V/m horizontal cloud discharge (Figure 4a), and 6% of ambient for a 40 V/m vertical return stroke (Figure 4b), at the respective altitudes of maximum ΔN_e. In both cases, the horizontal extent of the ΔN_e is much less than that of the heated region due to the highly nonlinear dependence of ΔN_e on E_{100} (Fig. 2). The north-south and east-west widths at half the maximum ΔN_e are 90 km and 70 km for the
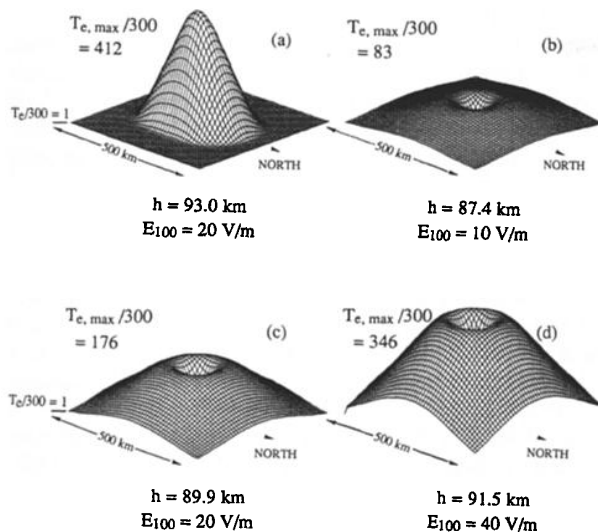

Fig. 3. Normalized heated electron temperature $T_e/300$ at altitude of maximum T_e over a 500 km x 500 km area centered over the source. (a) Source is a cloud discharge modeled as a horizontal dipole at 5 km radiating an EM pulse with peak field strength $E_{100} = 20$ V/m ($f = 30$ kHz). (b) Source is a return stroke modeled as a vertical dipole at 0 km radiating an EM pulse with peak field strength $E_{100} = 10$ V/m. (c) Same as (b), but for 20 V/m ($f = 5$ kHz). (d) Same as (b), but for $E_{100} = 40$ V/m. In all cases, the ambient N_e is given by profile b (Fig. 1). Geomagnetic north is indicated.
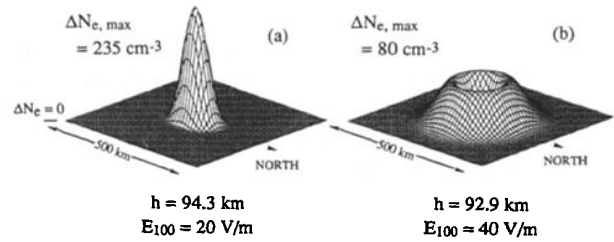

Fig. 4. Secondary ionization ΔN_e after a single ionization cycle at altitude of maximum ΔN_e over a 500 km x 500 km area centered over the source. (a) Source is as in Fig. 3a. (b) Source is as in Fig. 3b. In both cases, the ambient N_e is given by profile b (Fig. 1). Geomagnetic north is indicated.

horizontal discharge. The width at the outer half-maximum is 260 km for the vertical discharge.

4. Discussion

The VLF subionospheric reflection height is approximately where $\omega_p^2/\nu_o \simeq 2.5 \times 10^5$ s^{-1} (80.3 km for profile b, Fig. 1) [*Inan*, 1990]. For low P_d the altitude of maximum heating is near the ambient reflection height, where absorption is maximum [*Inan*, 1990]. The altitudes of maximum heating and ionization by a lightning pulse (Figs. 3, 4) are well above 80.3 km due to the self-action of the pulse. As the leading edge of the pulse begins to be reflected, the ionosphere around the ambient reflection height is heated, increasing the collision frequency ν and thus the reflection height. Successive portions of the pulse thus encounter an increasingly higher reflection height, leading to a higher altitude of maximum heating. Accurate modeling of the time-evolution of the reflection height is beyond the scope of this paper since we leave out reflection processes in our formulation, as mentioned above.

At the termination of the pulse, ν returns to its ambient value within ~ 10 μs [*Inan et al.*, 1991], so that subionospheric VLF perturbations lasting 10-100 s with onsets within <20 ms of lightning [*Inan et al.*, 1988] are probably signatures of electron density changes due to heating rather than of increased ν. Heating by an EM pulse from lightning may create alternating layers of electron density depletion and enhancement, or depletion only, in the D region [A. V. Phelps, private communication, 1991] since depletion (caused by dissociative attachment of electrons to O_2) and secondary ionization through electron-neutral collisions are competing processes whose relative effectiveness depends sensitively on the local E-field and number density of neutrals [*Gurevich*, 1978, pp. 79, 117]. Both electron density enhancement and depletion may be consistent with subionospheric VLF perturbations.

Although the horizontal orientation of some cloud discharges enhances their ability to heat the D region, more ionization cycles occur during the longer-duration EM pulses from return strokes. Furthermore, there may be more sufficiently intense EM pulses from return strokes than from cloud discharges. Recent experiments indicate that 40% of negative return strokes in winter storms are preceded by intense leader radiation; although the total number of negative return strokes is much larger in summer storms, a smaller percentage are preceded by intense leader radiation [*Brook*, 1992]. (Intense leader radiation generally is not observed to precede positive return strokes [*Brook*, 1992], which comprise 5% of return

strokes in summer and 50% in winter [*Orville et al.*, 1987].) On the other hand, the ratio of cloud flashes to CG flashes is 3-4:1 for the continental United States [*Prentice and Mackerras*, 1977], and intense pulses from intracloud flashes have been observed [*Willett et al.*, 1989] although statistics are not available on their intensities.

The predicted extents of the heated and ionized regions (Figs. 2, 3, and 4) are roughly consistent with the observation by *Boeck et al.* [1992] of a thin (10-20 km in vertical extent), broad (~500 km in transverse extent) airglow brightening at 95 km altitude above a lightning flash. Because optical excitation of neutrals occurs at lower electron temperatures than ionization, the transverse width at half-maximum of the airglow enhancement in the cases of Figure 4 should be greater than 90 km (horizontal dipole) and 260 km (vertical dipole). A quantitative comparison of optical emission intensities expected from lightning-induced heating and those observed by *Boeck et al.* [1992] is given by *Taranenko et al.* [1992].

5. Summary

A simple formulation of the propagation and absorption in a magnetized collisional plasma of EM pulses from lightning describes the effect of discharge orientation and radiated electric field on the structure and magnitude of heating and secondary ionization in the *D* region. Radiation from most lightning discharges can heat substantially, but only the most intense ($E_{100} \geq 20$ V/m) are likely to cause ionization enhancements $\geq 10\%$ of ambient in a single ionization cycle. This dependence on radiated electric field is modified by the discharge radiation pattern: a horizontal cloud discharge tends to cause larger heating and ionization maxima while a vertical return stroke causes disturbances of larger horizontal extent. The lack of statistics on EM pulse intensities from cloud discharges, whether part of cloud-to-ground or intracloud flashes, prevents a further comparison of the effectiveness of return strokes and cloud discharges in heating the *D* region.

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