Early VLF Perturbations driver by lightning-EMP generated density perturbations in the ionosphere: Model results

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Abstract

We present 3D model results demonstrating the ability of lightning electromagnetic pulses (EMP) to generate electron density perturbations in the ionosphere that can be measured with narrowband VLF transmitters. The first model is a Finite-Difference Time-Domain (FDTD) simulation of EMP which calculates ionization, attachment, and optical emissions in the ionosphere due to lightning. Results show that both vertical (cloud-to-ground) and horizontal (in-cloud) lightning discharges can produce observable density changes and optical emissions known as elves, and further, that the Earth's magnetic field has a strong effect on optical intensity and spatial structure. Electron density changes calculated in the FDTD model are input into the second model, a Finite-Difference Frequency-Domain (FDFD) VLF wave propagation model. This FDFD model propagates a VLF transmitter signal under and through the disturbed region and determines the amplitude and phase variation at a receiver due to the perturbation. Results show that attachment alone, or attachment and ionization together, can cause measurable perturbations. The ability of horizontal discharges to produce measurable disturbances through attachment is consistent with observed optical effects, and has implications for the mechanisms of so-called early/fast VLF perturbations.

1. Introduction

``Early/fast'' events are perturbations of VLF transmitter signals caused by lightning-induced effects in the lower ionosphere [1]. The specific physical cause of these perturbations has been controversial. [2] suggested scattering of the VLF signal from the body of sprite columns, including backscattering, while [3] demonstrated that the disturbances scatter VLF largely in the forward direction (later confirmed by [4]). [5] used a full-wave electromagnetic model to show that in the altitude regions at which sprite halos occur, the heating and ionization produced by the combined quasi-electrostatic (QE) field and the lightning electromagnetic pulse (EMP) may be the underlying cause of early/fast events. In this paper, we present a new mechanism, involving the dissociative attachment process in the lower ionosphere, leading to creation of ionospheric regions of reduced density, due to the multiplicity of EMP radiation from many in-cloud discharges.

[6, 7] used a 1-D model to predict electron density perturbations and optical emissions due to lightning EMP. An often-overlooked feature of these results is the density-depleted region from 80-85 km altitude, caused by dissociative attachment to molecular oxygen ($O_2 + e^- \rightarrow O + O^-$). We postulate that many Early VLF perturbations are caused by scattering from the electron density-reduced region at 80-85 km altitude. For single, large-amplitude EMP pulses impinging on a tenuous ionosphere, the effects of attachment are overwhelmed by ionization at 85-90 km altitude. In a dense nighttime ionosphere, the depletion due to attachment can be proportionally larger. Similarly, as the amplitude of the input pulse is decreased, the effects of attachment become proportionally larger, due to the lower energy threshold (~5 eV) for attachment compared to ionization (~16 eV). Note that the threshold for attachment is even lower than that of optical emissions, which implies that its effects would be seen before optical emissions (which in turn would be observed before ionization).

In this paper we present model results to determine the electron density perturbation due to a lightning EMP, and the feasibility of attachment depletions to cause measurable VLF transmitter signal perturbations. The density perturbations are calculated using an FDTD model of the lightning EMP (described in the next section), while the VLF transmitter signal perturbations are calculated with an FDFD code, described in section 4.

2. EMP Model Description

We model the electromagnetic pulse (EMP) due to lightning using a Finite-Difference Time-Domain code. The code solves Maxwell's Equations simultaneously at every point in space and advances in time until the pulse reaches 200 km altitude. The simulation space extends from 70 to 195 km in altitude, and from -250 to 250 km in the x and y

dimensions. The lightning impulse is simulated as an electric dipole at a specified altitude above conducting ground at (x,y,z) = (0,0,h), where h is varied from 2-10 km for horizontal discharges and 0 km (on the ground) for vertical discharges. The dipole field is then calculated analytically at the 70 km lower boundary at each time step, and propagated upwards into the simulation space. This method saves simulation time by reducing the size of the space, and removes effects of the quasi-electrostatic (QE) field.

The model solves for the 3-component E and H fields, as well as currents due to electron and ion densities. Electron densities and collision frequencies are input into the model. Ionization and attachment are calculated at each point in space and time, and the resulting changes in the electron density are tracked. Optical emissions are calculated using look-up tables; i.e., a at a given point in space and time, a particular E-field intensity and electron density corresponds to pre-calculated and tabulated optical excitation coefficients. We vary the dipole altitude and current direction; the peak field strength E_{100} (defined as the field strength scaled to 100 km); the electron density and collision frequency profiles; and the viewing direction for observing optical emissions.

2.1 EMP Model Results

Figure 1 shows some example results using the EMP model. For these runs, a "tenuous" ionosphere is employed to simulate quiet nighttime conditions; however, this profile is slightly more dense that the tenuous profile used by [7], and so the results are not identical. In the figure, the left two panels show optical emissions (in N_2 first positive band system) and electron density changes from an E_{100} = 10 V/m pulse oriented horizontally. The second pair show the same for E_{100} = 15 V/m; the third pair are the same for E_{100} = 20 V/m, but in this case the dipole is oriented 90 degrees with respect to the first two. In the rightmost panels we simulate a vertical dipole with E_{100} = 25 V/m. The optical emissions are a camera view from the ground, looking up at an 18-degree angle from a distance of 400 km, with a 9 x 18 degree field-of-view. The electron density results are a 2D slice through the center of the fully 3D results in the plane of the magnetic field, which is oriented at 67 degrees above horizontal as shown.

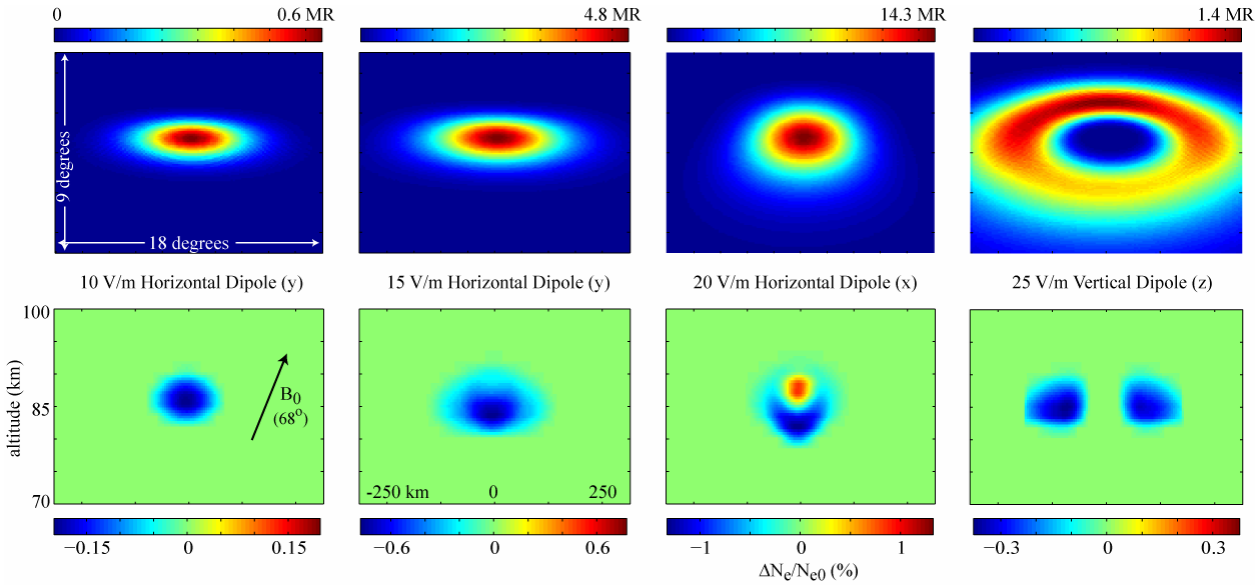

Figure 1: Elves and associated density perturbations. The top row shows optical emissions for the dipole situation noted below each figure. The bottom row shows associated electron density changes, as a percent change from the ambient profile. See the text for a full discussion.

A number of observations are evident. In the horizontal dipole simulations, ionization does not appear until 20 V/m (an unrealisitically high field for horizontal discharges) – this implies that for this ionosphere, horizontal discharges less than 20 V/m will not cause any ionization. Second, the optical emission intensity increases rapidly with field intensity, from 0.6 MegaRayleighs (MR) at 10 V/m to over 14 MR for the 20 V/m pulse. The orientation of the 20 V/m pulse demonstrates the "oval" shape of the field pattern from a horizontal dipole – note that it is rotated compared to the previous two. Furthermore, it can be seen that the magnetic field of the Earth plays a significant role in the real shape of the elve from a vertical dipole, as electrons are more easily accelerated along the field line.

3. Propagation Model Description

To model the VLF transmitter signal propagating in the Earth-Ionosphere waveguide, we employ a Finite-Difference Frequency-Domain (FDFD) code described in [8]. This code uses a segmented long path (SLP) method to efficiently simulate large spaces, in this case up to 5000 km in length. The SLP method breaks the space up into slabs of smaller thickness (here ~150 km) and calculates the fields for these smaller segments one at a time. The output of the first segment is then used as input for the following segment, and this process is repeated until the desired simulation distance is reached.

The model includes the Earth's ambient magnetic field, real ground conductivities over the surface of the Earth, and an ionosphere (electron density, ion density, and collision frequency) that can be fully specified in two or three dimensions. In this way, disturbances can be easily input by changing the electron density over a desired region. All runs described here at 2D.

3.1 Propagation Model Results

Many simulations have been run, using a variety of electron density profiles, disturbance profiles, disturbance locations along the signal path, and so forth. In this summary paper we present an example simulation to show the separate effects of attachment and ionization disturbances on the signal propagation.

Results are shown in Figure 2. Four runs are shown: (1) an ambient run; (2) an attachment run, in which we impose a depleted region; (3) an ionization run, in which ionization is imposed at higher altitudes; and (4) a ``realistic'' run with both attachment and ionization. The various profiles are shown in the inset, where the combined profile comes from [5] and the split profiles are simply the separated effects. These are not meant to be particularly realistic but rather to separate and quantify the effects of attachment and ionization. In all cases the perturbation has a gaussian profile in the propagation direction with a 1/e width of 40 km. The run length of 5000 km was chosen so that the perturbation could be located a realistic distance from the ``receiver'' (700 km from the end of the run) while avoiding interference nulls along the ground in the signal pattern (as observed near 4000 km in this example).

The top two panels show the 2D ambient H-field for the component that would be measured by a VLF receiver (H perpendicular to the image) and the signal amplitude along the ground. These results have been shown to match those of the Long-Wave Propagation Capability (LWPC) code. The figure shows the 2D scattering pattern (lower left panels) for each of the three perturbed runs that would be observed by a receiver in dB. The lower right panels show the scattered signal, as the amplitude perturbation would be observed at any given point along the ground. If a receiver were placed at 5000 km, for instance, in the ionization-only run a perturbation of -1.5 dB would be observed; in the attachment-only run, a +0.3 dB perturbation would be observed. This is the most important result: attachment alone yields a measurable perturbation, and the perturbation amplitude is positive. Of course, this single example is not proof of the positive-polarity argument, but a variety of other model runs show a positive-amplitude trend; for length reasons they are not shown here. Furthermore, note that this run consisted of a density depletion of 99% at 80 km, while the EMP model runs above predict only 1% or less; the multiplicity of in-cloud lightning is thus an important factor. Note that the ionization runs involve an order of magnitude density increase from [5]; with a more realistic increase such as observed by [9], it is possible the VLF transmitter signal will be significantly less affected.

4. Summary

We have presented 3D model calculations of EMP fields and their effects on the lower ionosphere, predicting optical emissions and density perturbations consistent with previous results. These density perturbations are in turn shown to produce measurable VLF transmitter signal perturbations, even in the case of attachment without ionization. These model results demonstrate the feasibility of horizontal in-cloud lightning EMP pulses to account for early/fast VLF perturbations. However, the multiplicity of the in-cloud lightning is an important factor, as the amount of attachment produced by a single pulse may be insufficient to cause measurable perturbations.

5. Acknowledgments

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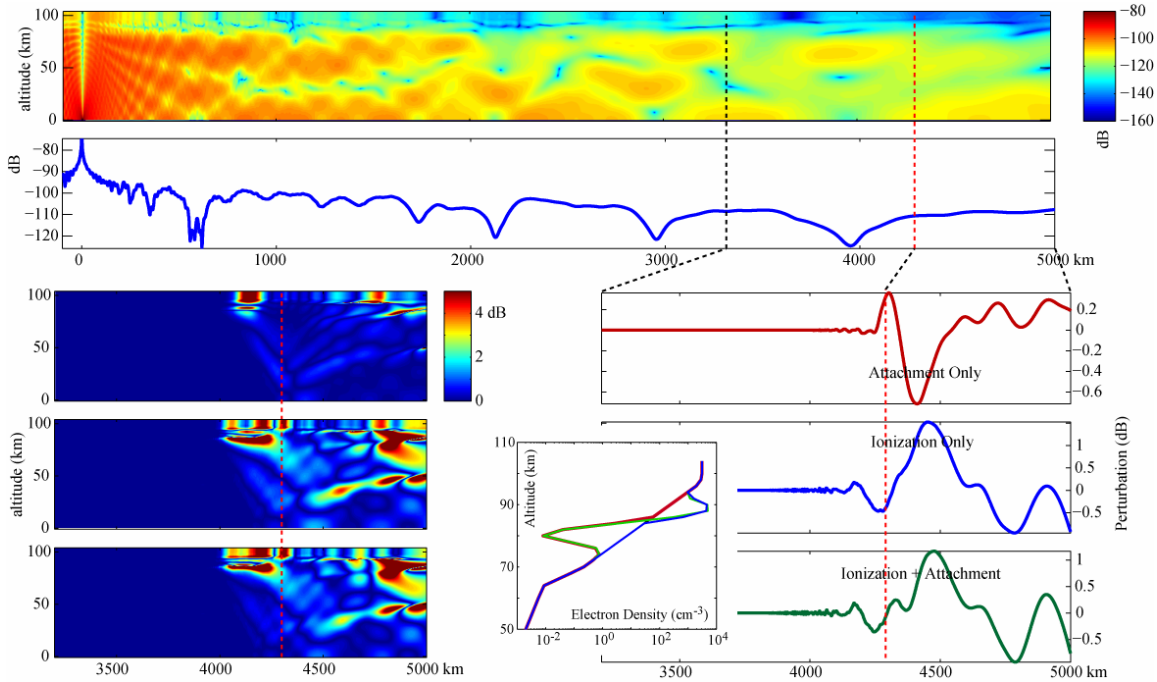

Figure 2: FDFD Model results demonstrating feasibility of attachment-caused VLF perturbations. Top panels: ambient VLF H_x field at 24 kHz in 2D and along ground; lower left panels: scattered fields due to three different profiles; lower right panels: ground signal for same three profiles; inset: the three profiles used, taken from [5]. The red dashed line shows the center of the perturbation, which has a gaussian *1/e* radius of 40 km.

6. References

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