NUMERICAL SIMULATIONS OF HIGH-ENERGY ELECTRON AVALANCHES IN THUNDERSTORM ELECTRIC FIELDS AND ASSOCIATED RADIO EMISSIONS

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ABSTRACT

We present the results of a one-dimensional model of an electron avalanche, initiated by a high-energy cosmic ray secondary electron, in a thunderstorm electric field. The processes included are ionization by the high-energy electrons, electron attachment, and the self-consistent evolution of the electric field. The time-evolution of the electron densities, characterized by mean energies of 7.2 MeV and 1-3 eV, and the associated radiation electric fields are reported. Relativistic effects are salient features of this model and can account for the peak radiation fields and VHF spectra of unusually intense cloud pulses observed from the Earth's surface.

INTRODUCTION

Using computer models and RF receivers, researchers at Los Alamos National Laboratory (LANL) have undertaken the study of radio emissions from lightning. In this report we review the observational characteristics of a subset of the radio pulses which are unusual because of their ~1-microsecond timescale, broadband spectrum and intensity. For data collected by a 26-48 MHz radio receiver onboard the FORTE satellite, typical source powers of these transient events are on the order of 100 kW [1]. Typical spectral amplitudes in this band range from about 10^{-9} to 10^{-6} $[(V/m)^2/MHz]$. The ionosphere acts as a high-pass filter, which reflects frequencies up to a maximum of about 30 MHz depending on the time of day [2]. Therefore it is expected that observations of these events from the ground could include lower frequency content than signals observed from space.

Ground-based observations of unusually intense VHF radiation associated with lightning using ground-based instruments are time-correlated with narrow bipolar pulses (NBPs). NBPs have reported durations ranging from a few to about 20 microseconds. They are of interest to the lightning community because their peak field strength is on the order of that observed during a first return stroke [3,4,5], making them unusually intense cloud pulses. The peak electric fields have been reported to be about 9.5±3.6 V/m at a range of 100 km [4].

Runaway breakdown is considered to be a viable mechanism for lightning initiation. Background levels of ~1-MeV cosmic ray electrons can avalanche in electric fields that are a factor of ten lower than those required for conventional breakdown [6]. If a sufficient ambient electric field exists over a large spatial scale, such as in a thunderstorm, a runaway electron avalanche can continue over a distance of hundreds of meters. Under such conditions the high-energy electrons of the avalanche produce measurable levels of x-ray photons via the Bremsstrahlung process. Modeled x-ray energy spectrums and count rates are in agreement with observations of x-ray bursts observed during thunderstorms [7]. This success motivates us to investigate the radio frequency radiation.

MODEL

A one-dimensional model has been developed to gain insight into the VHF radiation that can be produced by an avalanche event initiated by a single high-energy cosmic ray secondary electron. Detailed numerical solutions of a relativistic Boltzmann equation [8] have been performed to obtain the ionization rates and mean energies for an electron distribution evolving in various ambient field strengths at a 5-km altitude.

The mean energy of the high-energy electrons was found to be 7.2 MeV and is a weak function of the field strength. Because of this, the high-energy electron species is considered to be mono-energetic at 7.2 MeV and independent of the ambient field. The other dominant species is the low energy electrons. Their mean energy and drift velocity are functions of electric field, E, and pressure, P, as found from swarm experiments [9] and for thunderstorm conditions the average energy can vary between 1-3 eV. The production rate of these low energy electrons, R_s, is estimated to be $(\varepsilon_p/34\text{eV})\times R_p$ where R_p is the production rate of the high-energy electrons [10]. The energy expended in the production of an electron-ion pair is 34 eV. The dominant attachment rate for the low-energy electrons is three-body attachment, and dissociative attachment is also included in our analysis. For the simulations presented here the space charge field remains small compared with the ambient field. As the avalanche evolves, the ambient electric field can be reduced as the conductivity increases due to the production of a copious number of low-energy electrons. The electron density, which is taken to be uniform within a cylindrical channel, then becomes an important quantity for the one-dimensional model. For these preliminary results we estimate the channel radius to be 0.175m, which is an approximate radius for the conductive core of a stepped-leader channel [11]. The actual radius will be a function of the space-charge electric and magnetic fields, random walk diffusion, and the radial distribution of the electron density.

The ambient electric field is modeled as that from two spherical charges of opposite sign each with a radius of 500 m. The charge centers are separated by 2 km. Total charges for each sphere of ±10 and 30C are presented for comparison. The field varies with distance as given by Gauss's Law for spherical charges of uniform density. The atmospheric pressure is allowed to vary as given by the 1964 ICAO Standard Atmosphere [12].

The currents of the high and low-energy electrons are calculated and the radiated electric fields are found as a function of observer angle. Our numerical results for the peak radiated electric field as a function of angle have been tested against an analytic result [10]. For all observation angles the numerical calculation is within ±26% of the analytic result and we expect that our field calculations for the general cases will give roughly the same percent error.

RESULTS AND CONCLUSIONS

We present the results of two cases in which the thunderstorm charge is allowed to be ±10 and ±30 C for comparison. In both cases a cosmic ray generated, high-energy electron has a velocity anti-parallel to the ambient electric field near the lower negative charge region. Fig. 1 shows the ambient field as well as the low-energy and high-energy electron densities as a function of time, respectively.

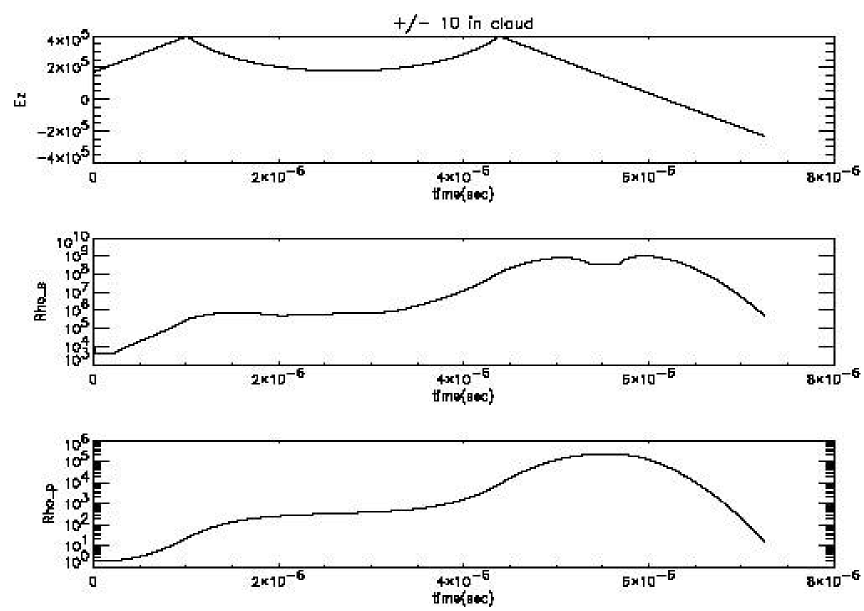

Fig. 1. ±10 C case: Vertical ambient electric field (Ez), low-energy (Rho_s) and high-energy (Rho_p) electron densities as a function of beam travel time.

The plotted time is the distance traveled by the high-energy electron density peak divided by βc. The avalanche rate is dependent upon the ambient electric field and with this level of charge in the model storm the field is a substantial fraction of 1MV/m for much of the path covered by the avalanche. Though this is a strong field in comparison to what is typical for thunderstorms [13], the high-energy and low-energy electron densities do not reach a level, which will produce substantial radio emissions. The ambient field is unaltered within the beam.

The results are substantially different for the ±30 C case. Consider Fig. 2. The ambient electric field within the beam is eliminated after the beam has traveled for less than 2µs. This is a dramatic difference and can be understood qualitatively. The avalanche rate is roughly proportional to the ambient electric field. The number density of electrons increases exponentially with avalanche rate. Therefore, by doubling the external field one squares the number density of electrons. However, when the field is tripled, as it has been here, the number density does not further increase. This is because high numbers of low-energy electrons increase the conductivity such that the electric-field relaxation time is short compared with the avalanche time. In this simple model the avalanche gradually comes to a halt when the beam passes the center of the positive charge region. The electric field is parallel to the velocity of the beam and the beam collision rate is increased. This in turn increases the production rate of low-energy electrons and decreases the production rate of high-energy electrons. It is not clear that this estimate correctly describes the decay of the avalanche, but our current emphasis is on characterizing the rise time and peak electric field of the avalanche.

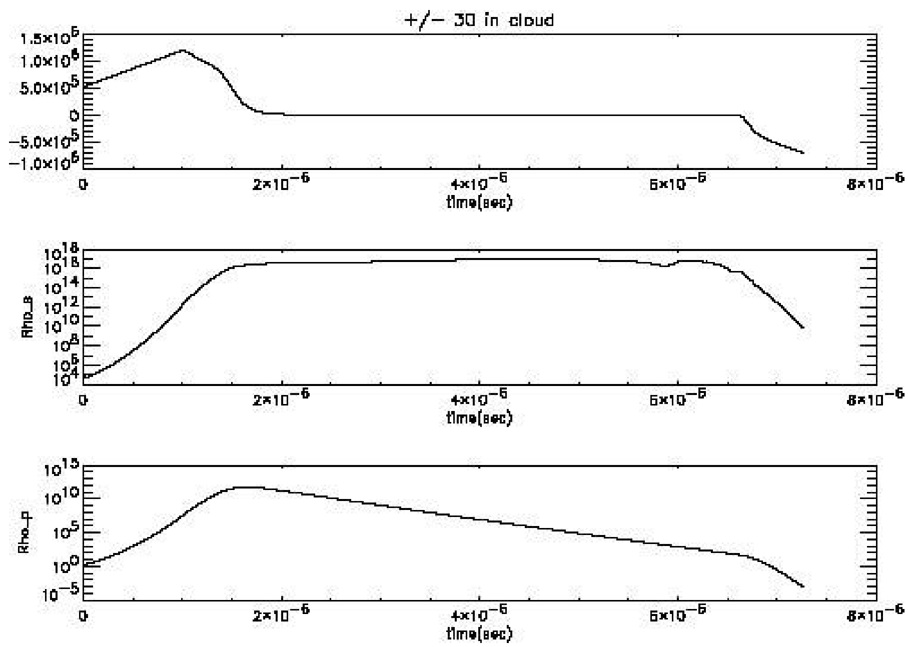

Fig. 2. ±30 C case: Vertical ambient electric field (Ez), low-energy (Rho_s) and high-energy (Rho_p) electron densities as a function of beam travel time.

Fig. 3 shows the radiated electric field waveform and spectral amplitude for the ±30 C case for an observation angle of 10 degrees. It is interesting to compare the peak amplitude to that found for NBPs. For a range of 100-km, a peak field of about 1V/m is expected. This is within an order of magnitude of the peak fields obtained observationally. The spectral amplitude of the VHF radio emissions at this angle is slightly high compared with observations made by the FORTE satellite in the 26-48 MHz band. If the beam were moving downward instead of upward, i.e. the positive and negative charge centers were reversed, a ground observer would record peak electric fields and VHF radiation fields much like those observed for NBP events. On the other hand, satellite observations of the TIPP events consist of two pulses: one is attributed to radiation that travels directly to the satellite and the other is attributed to a ground reflection [14,15]. For the conceptual model presented here, this could only be seen if the avalanche were traveling horizontally instead of vertically. Because this may not be true in general, other possible mechanisms of VHF emission that invoke either the runaway discharge or laboratory spark models should be considered for future research.

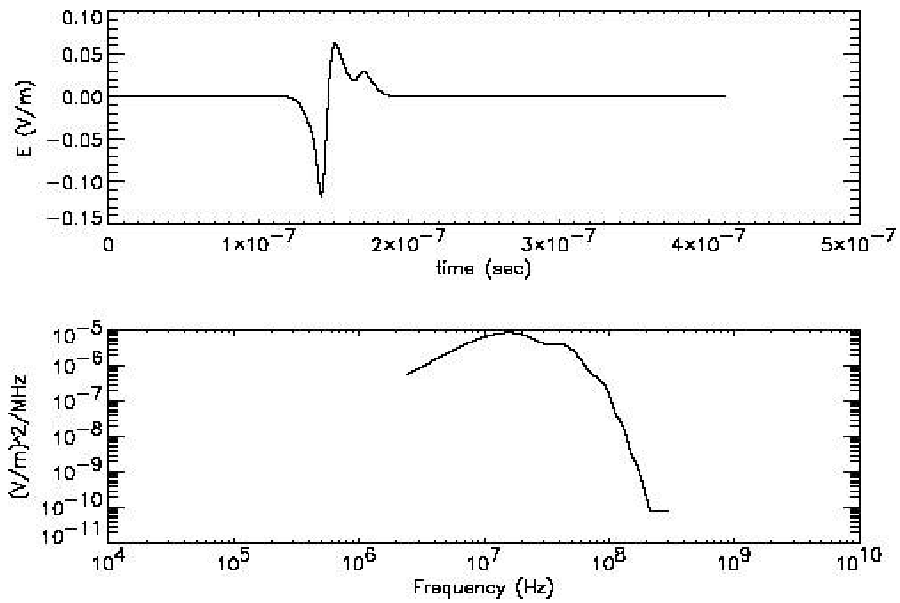

Fig. 3. ±30 C case. Top plot: High-energy electron radiation electric field at an 800-km range. Bottom plot: spectral amplitude [$(V/m)^2$/MHz] also at an 800-km range.

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