Downward emission of runaway electrons and bremsstrahlung photons in thunderstorm electric fields

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[1] Intensive radiations presumably associated with lightning activities have sometimes been detected around nuclear facilities in Japan. In order to investigate the generation of bremsstrahlung photons caused by thunderstorm electric fields, we calculated the behavior of secondary cosmic ray electrons and photons in electric fields by Monte Carlo technique. The photon flux increased greatly in the region where the field strength exceeded $280(\rho(z)/\rho(0))$ kV/m, and the photon energy spectrum showed a large increase in the energy region of several MeV. These are consistent with the observed results during the winter thunderstorms. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3230 Mathematical Geophysics: Numerical solutions; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning. **Citation:** Torii, T., T. Nishijima, Z.-I. Kawasaki, and T. Sugita (2004), Downward emission of runaway electrons and bremsstrahlung photons in thunderstorm electric fields, *Geophys. Res. Lett.*, *31*, L05113, doi:10.1029/2003GL019067.

1. Introduction

[2] Recently intensive gamma-rays generated inside thunderclouds have been observed in experiments using detectors mounted on airplanes, balloons, and a satellite [*Parks et al.*, 1981; *McCarthy and Parks*, 1985; *Eack et al.*, 1996a, 1996b; *Fishman et al.*, 1994]. The fluctuations of the cosmic ray intensity on the ground which seem to originate from thunderstorms have also been detected in mountainous areas [*Brunetti et al.*, 2000; *Chubenko et al.*, 2000; *Moore et al.*, 2001; *Takami et al.*, 2001]. Additionally, the gamma ray dose-rate increases associated with winter thunderstorm activities have been observed around nuclear facilities facing the Sea of Japan (the Hokuriku district) [*Torii et al.*, 2002]. The dose-rate enhancements we observed had the following features: (1)The durations of such enhancements were up to about one minute; (2)The affected areas seemed to be quite local, because in most cases, only one or two of the measuring instruments situated several hundred meters away from each other showed dose-rate increases at the time of lightning activity, sometimes with a lag of 10–20 seconds. Simultaneous gamma-ray bursts detected by all instruments installed around the site rarely took place; (3)The energy of the photons seemingly coming from the thunderstorm activities were up to several MeV. (4) The phenomena were observed only during winter thunderstorms.

[3] The first two features indicate that the observed phenomena can be attributed to the strong electric field inside thunderclouds, not to the individual lightning discharges. *Gurevich et al.* [1992] suggest that such energetic electrons as secondary cosmic rays are accelerated by the strong electric fields to trigger the runaway breakdown, namely an avalanche-type increase of runaway electrons, and this results in X-ray bursts due to the bremsstrahlung emission associated with the runaway electrons. Therefore, we have investigated whether the runaway electrons are generated inside the thunderclouds, especially in their lower parts, and whether such bremsstrahlung photons can be detected on the ground like those we observed during the winter thunderstorms.

[4] In this paper, we report the results of Monte Carlo simulations of the runaway breakdown process inside and under the thunderstorm electric fields using the electron and photon transport Monte Carlo calculation code EGS4 [*Nelson et al.*, 1985].

2. Electron-Photon Transport Calculation in the Thundercloud Electric Field

[5] For the acceleration of electrons by a thunderstorm electric field against the collisions with air molecules, the following requirement must be satisfied:

$$\frac{d\vec{p}}{dt} = e\vec{E}(z) - F(\rho(z), \vec{p}) > 0$$

where e is the electron charge, $E(z)$ and $\rho\ (z)$ are the electric field strength and the atmospheric density at the altitude z, respectively, p is the momentum of electron, and $F(\rho(z), p)$ is the frictional force that the electron experiences through collisions with air molecules.

[6] In a strong electric field, energetic electrons are accelerated to generate copious secondary electrons through collisions with air molecules. Consequently, these phenomena produce a shower of electrons and photons. To analyze the transport of energetic electrons by such electric fields

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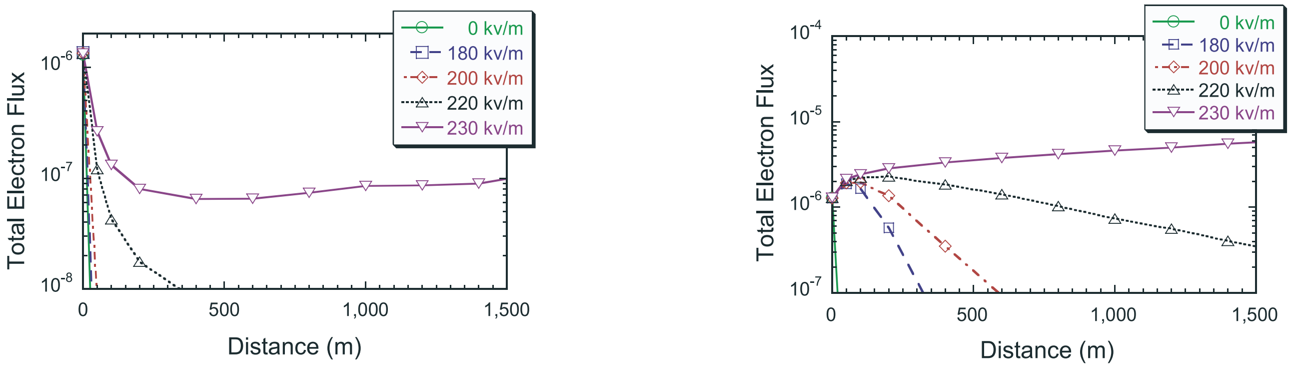

Figure 1. Calculated electron flux in the atmospheric density of 2 km altitude, plotted as the function of the distance from the radiation source where 1 MeV (left) and 10 MeV (right) electrons are emitted.

and estimate the condition for the generation of the runaway electrons, we modified the EGS4 code by embedding a subroutine, based on the Bielajew's manner [*Bielajew*, 1987; *Torii et al.*, 2000] for evaluating the influence that the external electric field has on electrons, and calculated the fluctuation of the total flux and energy spectrum of the bremsstrahlung photons generated in winter thunderstorm electric fields.

3. Results and Discussion

3.1. The Generation of Runaway Electrons and Bremsstrahlung Photons

[7] To make an estimation of the electric field strength required for the generation of runaway electrons in thunderclouds, we first calculated the fluxes and spectra of electrons and photons in the presence of monoenergetic electrons emitted inside a uniform electric field. Here, we defined the atmospheric density as those at the altitudes of 0 m(ground-level), 2 km, 5 km, and 10 km taken from the U.S. Standard Atmosphere 1976, and chose 1 MeV and 10 MeV electrons as the incident particles, since the frictional force on electrons is at a minimum when the electron energy is around 1 MeV [*ICRU*, 1984].

[8] Calculated total flux of electrons in the atmospheric density corresponding to the altitude of 2 km is given in Figure 1. The result clearly shows that the total electron flux increases with the distance from the electron source when the electric field strength exceeds 230 kV/m, which is inferred to be the minimal electric field strength E_{th} required for the generation of runaway electrons at this altitude. From the results corresponding to the ground-level, 5 km altitude and 10 km altitude, we deduce that E_{th} for each altitude is 280, 170, and 100 kV/m, respectively. Next, we present in Figure 2 the calculated variations in the electron and photon spectra at the altitude of 2 km under the field strength of 230 kV/m. It is obvious that the electrons are well accelerated within 200 m from the source point and producing bremsstrahlung photons with the energy of up to 10 MeV. We have, moreover, obtained similar results from the calculations corresponding to the other altitudes when the electric field strength exceeds E_{th}. These results are consistent with observation results of *Torii et al.* [2002] showing dose-rate increases of photons in the same energy region as mentioned in Section 1, and indicate that an avalanche-type increase of runaway electrons could lead to such phenomena. On the other hand, the calculation results corresponding to E_c, the critical electric field strength proposed by *Gurevich et al.* [2001], show that the electrons and photons keep losing energy and fade away as they travel several tens and hundreds of meters, respectively. All the above results suggest to us that

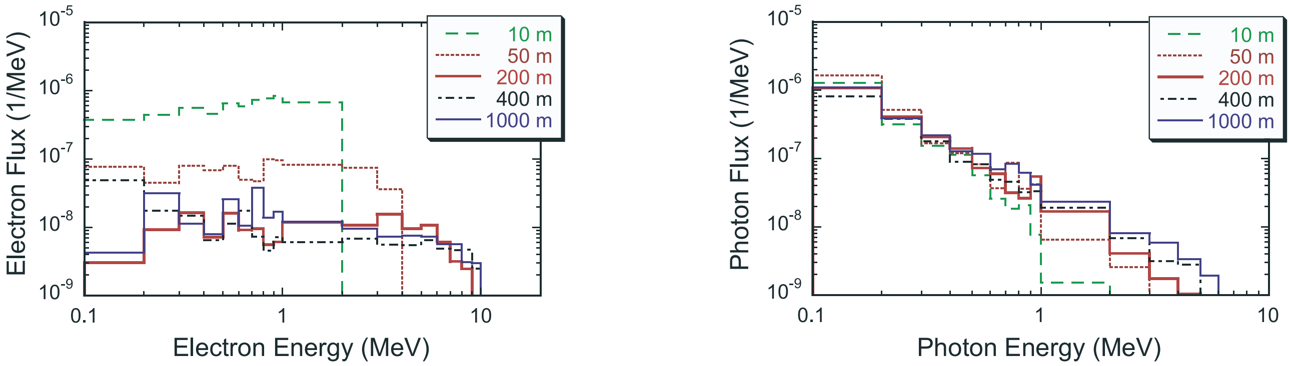

Figure 2. Electron (left) and photon (right) spectra at various distances from the radiation source where 1 MeV electrons are emitted. The atmospheric density corresponds to the altitude of 2 km, and the 230 kV/m external electric field is applied.

$E_{th} \approx 280(\rho(z)/\rho(0))$ kV/m, and it is 1.3 times greater than E_c. Here, $\rho(0)$ is the atmospheric density at the sea level.

3.2. Simulation of Bremsstrahlung Photon Behavior Inside and Below the Thunderclouds

[9] Following the simulations described in the previous section, we calculated the photon flux at various altitudes assuming that the secondary cosmic rays (photons, electrons, and positrons) are emitted downward at the altitude 6 km onto the thunderstorm electric field. Since it is considered that the thunderclouds form dipole or tripole charge structures even in winter [*Michimoto*, 1993], we modeled the vertical electric fields inside and below the dipole and tripole winter thunderclouds by using Finite Element Method, and adopted the models (depicted in Figure 3) in the Monte Carlo calculation.

[10] These electric field models are about ten times greater than the results of the balloon soundings from Japanese winter storms, $|E_{aloft}| \leq 30$ kV/m, shown by *MacGorman and Rust* [1998]. However, there were no lightning discharges from these storms, and some observations on the ground seem to support our models. For example, *Michimoto* [1993] present electric field measurements by a car-borne fieldmill on the ground below winter thunderclouds in the Hokuriku district, showing tens of kV/m magnitudes with the maximum 82 kV/m. In addition, it is known that lightning flashes from winter thunderstorms in this district often yield intense electric current which is an order of magnitude greater than that of summer lightning flashes [*Turman*, 1977; *Brook et al.*, 1982]. Therefore, we expect that such strong electric fields in winter thunderclouds as given in Figure 3 can be possible.

[11] As the energy spectrum parameters of the emission source, we adopted the energy spectra of the secondary cosmic ray particles (photons, electrons, and positrons) evaluated by *Daniel and Stephens* [1974].

[12] As illustrated in Figure 4, the photon flux in the tripole winter thundercloud model increases sharply around the altitude 1km, the lower part of the cloud, and remains several times greater than the other two results even below the cloud base. It is presumably due to the strong electric field of the tripole model exceeding E_{th} around this altitude. Such an electric field can lead to the avalanche-type increase of energetic runaway electrons and thus the generation of a significant amount of bremsstrahlung photons, some of which may reach the ground consequently causing the dose-rate increases we observed in conjunction with the winter thunderstorm activities.

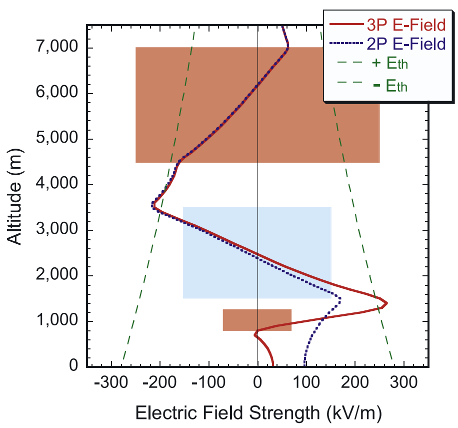

Figure 3. Electric field variations in the dipole and tripole winter thunderclouds and the threshold field strength E_{th} (broken lines). Rectangles represent charged areas (Top and bottom ones with positive charge and the middle one with negative charge).

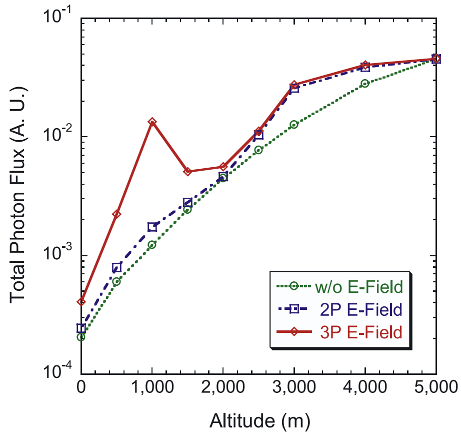

Figure 4. Calculated photon flux in the dipole (2P) and tripole (3P) winter thunderstorm electric fields and zero electric field(w/o), plotted as the functions of the altitude.

[13] From the simulation results described above, we can draw the following conclusions. In the tripole winter thundercloud, it is possible that runaway electrons and intensive radiation are generated in the lower part of the cloud where a strong electric field exceeding E_{th} exists, and then trigger the dose-rate increases such as those we observed on the ground. However, in the case of the summer thunderclouds and dipole winter thunderclouds, the altitude of the strong electric field region is thought to be considerably greater than the attenuation length of bremsstrahlung photons. So it seems that such thunderclouds rarely affect the dose-rate on the ground except in mountainous areas, because the bremsstrahlung radiation produced inside the strong electric field region is expected to attenuate in the atmosphere, as described in the previous paper [*Torii et al.*, 2002], so that near the ground it is hardly discernible above background levels.

4. Concluding Remarks

[14] In order to clarify the reason for the gamma-ray dose increases observed on the ground during winter thunderstorms, we have developed the Monte Carlo calculation code with the function of evaluating the effect of an external electric field, and calculated the behavior of energetic electrons and bremsstrahlung photons, assuming that the generation of such particles are triggered by the electromagnetic component of the secondary cosmic-rays incident on strong electric fields inside thunderclouds. However, the behavior of secondary cosmic-ray muons is not considered in this calculation. Since muons also form a large part of the secondary cosmic-rays, and directly reach the region of strong electric fields owing to their high penetrability in the atmosphere, they can serve as the source of a considerable

amount of runaway electrons, through their ionization of air molecules producing a number of knock-on electrons and the production of muon decay electrons. As the next stage of this work, we will carry out analytical evaluations of transport of cosmic-ray muons and associated electrons.

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