The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World
Chattanooga, Tennessee, April 17-21, 2005, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2005)

ENHANCED ELECTRON AND PHOTON FLUXES IN THUNDERSTORM ELECTRIC FIELDS AND THE INITIATION OF LIGHTNING DISCHARGE

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ABSTRACT

Gamma ray dose-rate increases associated with winter thunderstorm activities have been observed in the coastal areas facing the Sea of Japan. In order to investigate the generation of energetic photons which originate in thunderstorm electric fields, we have calculated the behavior of energetic particles in such electric fields with the Monte Carlo method. In the calculation of MeV electrons emitted in the atmospheric air, the electron and photon fluxes have increased greatly in the region where the field strength exceeded $280\ P\ (z)$ kV/m, and the photon energy spectrum showed a large increase in the energy region of several MeV. We have also carried out the Monte Carlo calculation of the cosmic-ray muons and associated particle transport in the thunderstorm electric fields. It has been confirmed that the electron and photon fluxes are incredibly increased in the strong electric field simulated thunderclouds, while the muon flux does not fluctuated significantly. From these results, it is seemed that the energetic electrons induced by cosmic ray muons are a key role of the enhanced electron and photon fluxes in thunderstorm electric fields. These results indicate that the production of secondary electrons plays an important role in the intensive ionization of the air, and as a result a significant growth of electric conductivity in thunderstorm electric fields. These productions may also induce the lightning discharge by these processes. Furthermore, we discuss the simulation of the beta and gamma rays emitted by radon progeny products as the other source of energetic electrons in the atmosphere.

Key Words: Thunderstorm, Runaway Electron, Muon, Radon Progeny, Triggered Lightning

1 INTRODUCTION

Fluctuations in radiation intensities within or above thunderclouds have occasionally been observed in recent years by aircrafts, balloons and an artificial satellite equipped with radiation detectors [1, 2, 3]. Fluctuations in cosmic ray intensities have also been observed in mountain areas. Furthermore, the environmental radiation monitors and other radiation detectors installed in the vicinity of nuclear power stations along the coast of the Sea of Japan are known to report radiation dose increases exclusively during thunderstorms in winter [4, 5]. Using the Monte Carlo calculation code EGS4 [6], we simulated the behaviors of electrons and photons originating from cosmic rays or from radon progeny products within the electric field of a typical winter thunderstorm. According to the results of our simulative analysis, the production of secondary electrons and photons increases with electric field intensity, and continuous production of electrons and photons occurs and causes an electromagnetic shower when the electric field strength exceeds $280\ P(z)$ kV/m, where $P(z)$ is the atmospheric pressure (atm) at altitude z (m) [7]. At the same time, we have ascertained through our calculations that cosmic-ray electrons and photons produce bremsstrahlung radiation of up to several MeV, a part of which can reach the ground.

Since cosmic-ray muons form a large part of energetic charged particles 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 electrons through their ionization process with air molecules and their decays. Focusing on muons as a major component of cosmic rays, we studied the fluctuations experienced by particle fluxes within a thunderstorm electric field by simulating the behaviors of muons and knock-on electrons using the Monte Carlo calculation code GEANT4 [8], the results of which are reported in this paper.

This paper also discusses the fluctuations experienced by electron and photon fluxes originating from radon progeny products. The contribution of radiation to the initiation of a lightning discharge and the feasibility of lightning induction using a high energy muon beam are also discussed considering rapid increase of electron density due to the injection of high-energy charged particles into the electric field of thunderstorm.

2 CALCULATION AND RESULTS

2.1 Behavior of cosmic-ray muons and knock-on electrons within thunderstorm electric fields

As charged energetic particles that exists popularly in the atmosphere, we analyzed the behaviors of cosmic-ray muons, knock-on electrons generated by cosmic-ray muons when they collide with air molecules, and the electrons produced by muon decay within a thunderstorm electric field using the GEANT4 code. Here, we assumed the cylindrical triple-pole structure given in Fig. 1 when we simulated the distribution of electric charges in a typical winter thundercloud, and determined the distribution of electric field intensities over different altitudes using the finite element method.

At this time, we segmented altitude into units of 500 m for distances of up to 10 km above ground, and into units of 1 km for distances of 10 to 15 km above ground, so as to assign different atmospheric densities according to the US Standard Atmosphere. The energy spectra of cosmic-ray muons were determined using the evaluated values given by Coutu et al. [10]; we calculated electron and photon fluxes at different altitudes assuming downward emission of muons from an altitude of 12 km.

Fig. 2 shows the altitudinal distributions of the fluxes of muons, associated electrons, and photons with/without the tri-pole structural electric field. The results demonstrated no significant change in muon fluxes in a thunderstorm electric field, as same as the case without electric field. However muons have been shown to cause a significant increase in electron and photon fluxes within a strong electric field through the contribution of knock-on electrons produced by the travel of muons. Since muons 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. It seems that these properties contribute the increase of electron density within a thundercloud, as well as the generation of energetic radiation observed above and below thunderclouds.

2.2 Electron and photon fluxes generated by beta ray emissions from radon progeny products

To estimate the energetic particle transport within a thundercloud in the presence of beta and gamma rays emitted from radon progeny products, we have calculated the behavior of electrons and photons inside and under the thunderstorm electric fields using EGS4 code. As shown in the previous calculation, we have also used the tri-pole electric field model of a winter thundercloud. In view of the typical states of the atmosphere during a thunderstorm, we have assumed a uniform density of radon progeny products in spaces up to an altitude of 2 km, where a strong electric field should prevail, and simulated the releases of beta and gamma rays in 4π directions [11].

As the typical results, Fig. 3 shows the altitudinal distributions of photon and electron fluxes originating from the beta and gamma rays emitted by Bi-214. Even though the distributions show a slight increase in photon fluxes in the region with a strong electric field, the electron flux shows a significant increase in the same region. From the result, it can be suggested that the cause of an increase in gamma ray intensity observed near the ground is the cosmic ray components rather than radon progeny products.

3 ENHANCED ELECTRON AND PHOTON FLUXES AND LIGHTNING INITIATION

This section discusses the fluctuations experienced by electron fluxes in the presence of a thunderstorm electric field. With the electromagnetic components of cosmic rays and muons as well as with beta and gamma rays from radon progeny products, the presence of a strong electric field causes a dramatic growth of electron fluxes, which is more significant than the increase of photon fluxes. In particular, the increase of energetic electrons is significant.

While the electric field strength necessary for producing an air breakdown has been identified as 3 MV/m in laboratory experimentation (using parallel plate electrodes), an electric field of such strength has not been observed in a thundercloud; the typical electric field strength in a thundercloud is an order of magnitude less than the threshold electric field of conventional breakdown. This means that the mechanism behind the initiation of lightning discharge is still not clear. Gurevich et al. [9] have characterized the difference from a conventional breakdown by the presence of runaway electrons; such runaway electrons are produced by the acceleration of cosmic-ray electrons in the atmosphere and can produce a particular type of breakdown called runaway air breakdown. Our analysis has also confirmed the possible occurrence of an electromagnetic shower at an electric field strength lower than the conventional breakdown requirement by almost an order of magnitude, which can produce an increase of electron flux over two digits, and an increase of electrons with energy of several MeV in particular. These results suggest as follows:

- In the region with a strong electric field in thunderclouds, cosmic rays and beta/gamma-rays from radon progeny products can trigger the production of a large number of energetic electrons.
- Since the W-value of air is about 34 eV per electron-ion pair, energetic electrons can produce a large number of electron-ion pairs as they are absorbed in the air.
- The production of a large number of electron-ion pairs should increase the electric conductivity in the region with a strong electric field, which may boost the initiation of a lightning discharge.

4 FEASIBILITY OF MUON TRIGGERED LIGHTNING INDUCTION

Based on the above mentioned, this section discusses the feasibility of a lightning induction method that takes advantage of the high penetrability of muons and the production of a large number of knock-on electrons by muons.

As in the calculations mentioned in earlier sections, we have assumed a cylindrical tri-pole structure (5 km in radius and 15 km in height) for simulation of the electric charge distribution within a typical winter thundercloud. At this time, however, we have simulated a case in which 2 GeV muons are emitted toward the thundercloud at the elevation angle of 30 degrees from a point on the ground 7.5 kilometers away from the central axis of the thundercloud. Fig. 4 shows the muon tracks obtained by a simulation by the GEANT4 code. As shown in the figure, the muon beam is rapidly deflected as it enters a strong electric field within the thundercloud, producing a large number of photons generated.

Since a large number of secondary electrons are produced with photons, we calculated the energy deposition in the air by these secondary electrons and photons. Fig. 5 shows the energy deposition in the air per single particle of injected muons (calculated history number: 10,000). The x-axis plots the travel distance of a muon in its direction of travel, and the y-axis plots the energy deposition from the muon by the electrons and photons produced by it every 100 meters of its travel.

For comparison, the energy deposition without electric fields is plotted as well. In the case assuming the presence of thunderstorm electric field, it can be seen in this figure that the energy absorbed from a muon will be increased a dozen-fold or more at the point about 7 km away from the muon source in terms of traveling distance (approximately 6 km away in terms of horizontal distance), where the energy absorbed from a single muon will amount to 40 to 60 MeV. Therefore, it becomes that approximately 100 million electron-ion pairs are produced for one energetic muon injected in this area. These results are indicative of the feasibility of causing a sharp increase in the electron density within a thundercloud by emitting a collimated muon beam into a strong electric field within the thundercloud, thereby increasing the electric conductivity of that region to induce a lightning discharge.

5 SUMMARY

This paper reported on our application of Monte Carlo calculation codes in our simulative analysis of the behaviors of radiation within a thunderstorm electric field.

First, we carried out a Monte Carlo calculation to determine the effect of the thunderstorm electric field on cosmic-ray muons. The results of this calculation have shown that muons, as well as the electromagnetic component of cosmic-rays, can cause an increase in the electron and photon fluxes as the travel of muons within a strong electric field produces knock-on electrons, which produce a large number of secondary electrons. Since cosmic-ray muons are more penetrative than electrons and photons, and are also capable of releasing knock-on electrons as they travel, they can directly enter a strong electric field within a thundercloud and serve as a primary source of runaway electrons and bremsstrahlung photons.

Next, we performed a similar calculation regarding the effect of beta/gamma rays from radon progeny products. The results of this calculation did not demonstrate a significant increase in the photon flux density, while they did demonstrate an incredible increase in the electron flux. These results are indicative of the role of radiation in the initiation of a lightning discharge because they are shown to be capable of triggering an increase of electron density in the region with strong electric field.

Furthermore, we proposed and studied the feasibility of a new lightning induction method of artificially causing an electromagnetic shower by emitting a muon beam into a strong electric field within a thundercloud, thus facilitating the initiation of a lightning discharge. Our simulative calculations regarding this method confirmed its feasibility as the results indicated that the presence of a strong electric field will significantly increase the energy deposition in the air from the injected muons; the muons will emit a large number of electron and photon fluxes in such an electric field, increasing the electron density in the region to the effect of facilitating a lightning discharge.

To confirm the expectation mensioned in Sections 3 and 4, we are carrying out an experimental study on the behavior of energetic electrons in strong electric fields and the observation of radiation during thunderstorms.

6 ACKNOWLEDGMENTS

We wish to acknowledge cooperation of the collaborators of the Environmental Monitoring Section, Tsuruga Head Office, JNC, and the Lightning Research Group of Osaka University. One of the authors (T. Torii) is also grateful to Mr. H. Nishimura, Mr. K. Kishiwada, Dr. N. Nakae (JNC), and Prof. M. Nakazawa (Univ. of Tokyo) for their encouragement of this study.

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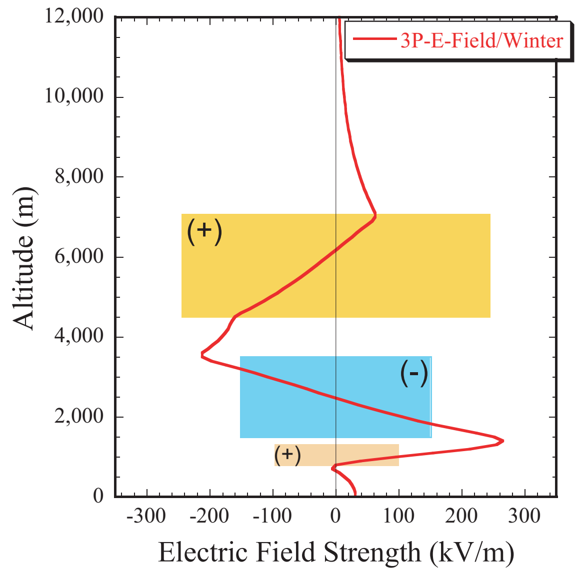

Figure 1: Tri-pole structure model of electric charges in a winter thundercloud and the altitudinal distribution of electric field strength.

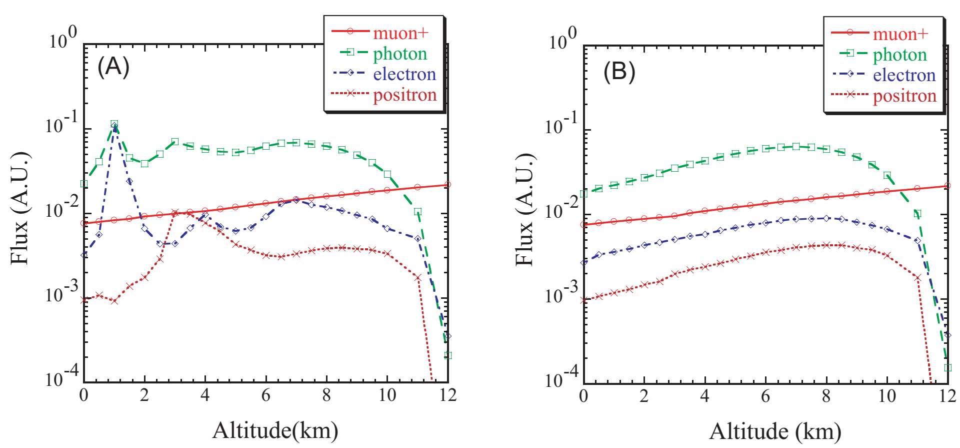

Figure 2: (A)Altitudinal distributions of muons, electrons, positrons and photon fluxes assuming the downward emission of cosmic-ray positive muons from an altitude of 12 kilometers in the case of the tri-pole structural electric field exists. (B)The fluxes in the case without electric field.

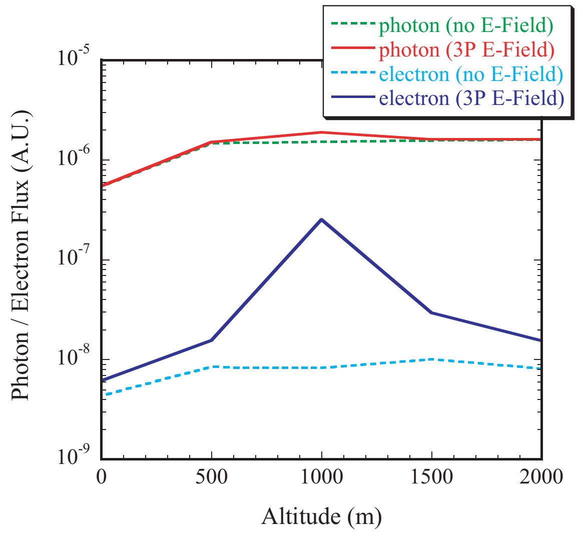

Figure 3: Altitudinal distributions of photon and electron fluxes assuming the uniform distribution of a radon progeny product (Bi-214) in spaces up to an altitude of 2 km.

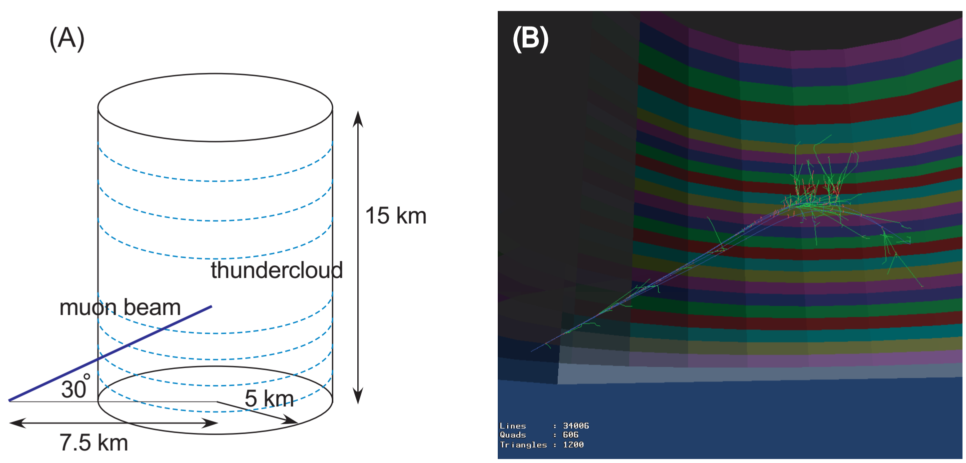

Figure 4: (A) Simulation model of muon irradiation, and (B) Simulated particle tracks of 2 GeV positive muons (blue) emited from the ground toward a thunderstorm electric field (for 5 muon emitted). Red ,and green lines in (B) are electron, and photon tracks, respectively.

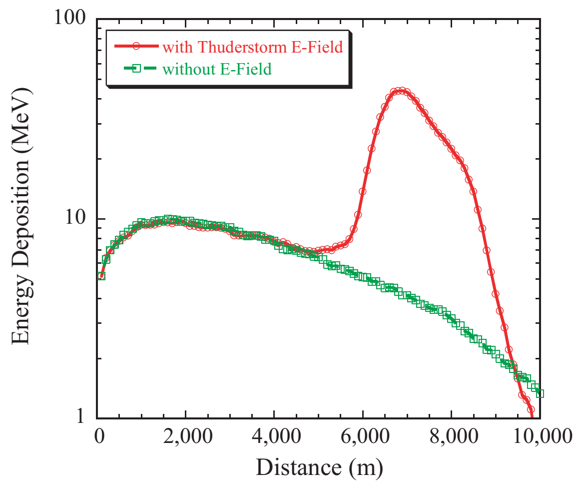

Figure 5: Energy deposition in the air from a positive muon injected into a thunderstorm electric field, and the deposition in the case without electric fields.