Monte Carlo Simulation for the Source of Transient Energetic Radiation Generated by Thunderstorm Activity

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Abstract. Intensive and transient energetic radiations associated with winter thunderstorm activities were detected around the west coast of Sea of Japan. We identified the source location of the transient energetic radiation, lasting for several minutes, through the observations of radiation, atmospheric electric field, and meteorological radar echoes. Our identification indicated that the transient energetic radiation was emitted from a downward hemispherical surface with regardless of lightning discharge, the bottom of which was about 300 m above sea level. This may occurs due to the generation of bremsstrahlung photons caused by electric fields inside the thunderstorm, because the energy of the observed radiation exceeds that of the radiation emitted from natural nuclides. In order to verify this speculation, we calculate the behavior of secondary cosmic ray electrons and photons in intensive electric fields by Monte Carlo technique. The photon flux largely increases just under the thundercloud if we assume that the electric field around the downward hemispherical surface is - 400 kV/m, and the photon energy spectrum shows a large increase in the energy region of several MeV. When the calculated energy spectrum emitted from the thunderstorm is consistent with the observed results, the large electric field around - 400 kV/m is required around the bottom of the thundercloud.

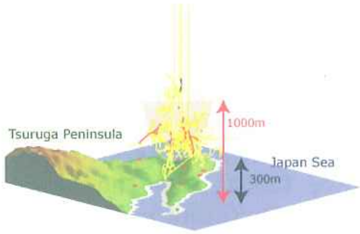

Fig. 1 Schematic diagram of the spherical source of radiation on 7 January 2010 (Torii et al., 2011). Circles drawn on the ground is observation points. Some of trajectories of the electromagnetic shower by means of Monte Carlo simulation are described.

Keywords: Transient energetic radiation, Monte Carlo simulation, Winter thunderstorm, Atmospheric electric field

1. Introduction

Energetic radiation possibly generated from thunderstorm and lightning discharge has been detected on the ground-based observations (Chubenko et al., 2000; Moore et al., 2001; Torii et al., 2002, 2011; Dwyer et al., 2005; Tsuchiya et al., 2007). Such radiation can be classified by its duration into two groups (Torii et al., 2008). One group is the instantaneous energetic burst (IEB) lasting for no more than a few milliseconds with energy generally up to several hundred keV. It is thought that these IEBs are produced in the process of lightning discharge including the stepped-leaders before the return stroke (Moore et al., 2001). The other group is the Transient energetic radiations (TER) with the duration of several seconds to several minutes and with the energy up to about 10 MeV. This type of radiation has been observed on high mountains (Brunetti et al., 2000; Muraki et al., 2004; Torii et al., 2009; Tsuchiya et al., 2009) as well as at sea level during winter thunderstorms in Japan (Torii et al., 2002, 2011). The TER is not attributed to individual lightning discharges, because no cloud-to-ground (CG) lightning had been observed when the TER was detected (Torii et al., 2009).

In order to explain the mechanism of the lightning initiation, Gurevich et al. (1992) suggested that energetic charged particles such as cosmic rays accelerated by an external electric field trigger the runaway breakdown, namely an avalanche-type increase of runaway electrons, so that this massive generation of runaway electrons results in the lighting discharge with the IEB caused by bremsstrahlung emission. According to their idea, the intensive electric field which causes the breakdown (~ 3 MV/m) is not required at the time of lightning initiation, and around 0.2 MV/m is enough to initiate the lightning if the accelerated path for the charged particles, termed characteristic length, exists sufficiently. According to Dywer (2004), the characteristic length λ at the standard temperature and pressure in SI unit is given by

$$\lambda = 7200 / (E - 275), \quad (1)$$

where E is the external electric field. Their idea of the runaway breakdown may be supported by the observation, because the observed electric field inside the thunderstorms at the time of the lighting initiation was approximately 200 kV/m at sea level (Marshall et al., 1995). Extending to the idea of runaway breakdown, we apply it to understanding the generating mechanism of the TER.

In our previous study, we identified a migrating source of TER, lasting for several minutes, attributed to thunderstorm activities through the observations of radiation, atmospheric electric field, and meteorological radar echoes at several points (Torii et al., 2011). Our findings of this study are as follows (see Fig. 1): The TER was emitted from a downward hemispherical surface without lightning. The bottom of the hemispherical surface was about 300 m above sea level. This source of radiation moved from north to south above the observation site with about 7 m/s velocity. The radiation source probably moved along with the charged region of the cloud at the height of around 1 km, because the estimated migration of the radiation source was consistent with the observed movement of atmospheric electric field variation between ground-based observation sites and with the wind speed and direction at about 1 km altitude. We concluded that the intensive electric field produced by the charged region in the thundercloud generated a radiation source beneath the charged region. In this study, we compute the intensity and energy spectrum of radiation under the condition of thunderstorm-generated electric field by means of Monte Carlo simulation to understand the observed values.

2. Incorporating the effect of external electric field to particle transport calculation

For electrons accelerated by a thunderstorm electric field with the collisions to air molecules, the following equation is satisfied:

$$\frac{d\vec{p}}{dt} = e\vec{E}(z) - F(\rho(z), \vec{p}) > 0 \tag{2}$$

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

In a high electric field, energetic electrons are accelerated to generate massive secondary electrons through the collisions with air molecules. Consequently, these phenomena produce a shower of electrons and photons. To compute the transport of energetic electrons inside the external electric field and estimate the condition for the generation of the runaway electrons, we modified the sub-routine ELECTR of the EGS5 code (Hirayama et al., 2005), applying the analytical method (Bielajew, 1997; Torii et al., 2000). The equation to calculate the direction vector, the position, and the final energy of electrons are shown as follows:

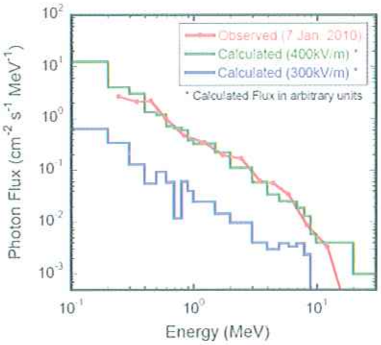

Fig. 2 Energy spectra of generated energetic photons in the thundercloud electric field with the surface electric field of -300 kV/m and -400 kV/m. It is also shown the observed spectrum of the energetic photons caused by the winter thunderstorm activity (see Torii et al., 2011).

$$\vec{u}_f = \vec{u}_0 + \Delta\vec{u}_{ms,ret} + \Delta\vec{u}_{em} \tag{3}$$

$$\Delta\vec{u}_{em} = \frac{es}{m_0\gamma(E_0)v_0^2}\left(\vec{D}_0 - \vec{u}_0\left(\vec{u}_0 \cdot \vec{D}_0\right) + \vec{v}_0 \times \vec{H}_0\right) \tag{4}$$

$$\vec{x}_f = \vec{x}_0 + \vec{u}_0 s + \frac{s}{2}\left(\Delta\vec{u}_{ms,ret} + \Delta\vec{u}_{em}\right) \tag{5}$$

$$E_f = E_0 - \Delta E_{ret} + e\vec{D}_0 \cdot \left(\vec{x}_f - \vec{x}_0\right), \tag{6}$$

where $\vec{u}_f$, $\vec{u}_0$, and $\Delta\vec{u}_{ms,ret}$, $\Delta\vec{u}_{em}$ are the final direction, the initial direction, the deflection due to multiple scattering and inelastic collisions, and the deflection due to electromagnetic interaction, respectively. Furthermore, e is the electron charge, and s is the motion of particle (step length). $\vec{D}_0$ and $\vec{H}_0$ mean the external electric and magnetic components of electromagnetic field, respectively. Also, m_0, $\vec{v}_0$, $\vec{x}_f$, and $\vec{x}_0$ are the mass and the initial velocity, the final position, and initial position of the electron, respectively. In addition, $\gamma(E_0)$ shows the Lorentz factor $(= (1 - \vec{\beta} \cdot \vec{\beta})^{-1/2})$. In addition, E_f, E_0, and ΔE_{ret} is the final energy, the initial energy, and the energy loss due to inelastic collisions, respectively. The detailed description of this methodology is shown in the reference (Torii and Sugita, 2005)

By using the modified EGS5, the behaviors of electrons and photons originating from cosmic rays and radon decay products inside the electric field of a winter thunderstorm can be simulated (Torii et al., 2004, 2005). According to this simulation analysis, the production of secondary electrons and photons increases with the electric field intensity, and when the electric field intensity exceeds about

280*P(z)* kV/m, where *P(z)* is the atmospheric pressure in units of atm at altitude *z*, then continuous production occurs and causes an electromagnetic shower. Furthermore, in the transport calculation of the electromagnetic component of cosmic-rays injected at the top of the winter thundercloud, the electron and photon fluxes increased in the intensive electric field region and the photon energy spectrum was enhanced in the order of MeV (Torii et al., 2004).

3. Monte Carlo Simulation of the case of 7 Jan. 2010

From the unfolding calculation for the pulse-height distribution of the UER event measured on 7 January 2010 (Torii et al., 2011), we obtain the energy spectrum of the radiation attributed to the thunderstorm (Fig. 2). An energy spectrum largely increases in flux around 3−7 MeV, when comparing of energy spectrum between the background radiation and the enhanced radiation. This enhanced spectrum is not attributed to atmospheric radioactive materials such as radon decay products.

The above results indicate that the intensive radiation consists of high-energy bremsstrahlung photons generated by the acceleration of secondary electrons due to electric field inside the thundercloud and is not caused by atmospheric radioactivity. In addition, it may be noted that the radiation is emitted for a long time, *i.e.*, several tens of seconds or more. In the observation, no CG lightning was observed during the time period when the long burst was measured, as already reported (e. g., Torii, et al. (2002) and Torii et al. (2009)).

In order to simulate the radiation associated with thunderstorms activities, we calculate the variations of the energy spectrum of photons when cosmic-ray photons with $1/E^{1.4}$ energy spectrum (Sato et al., 1995) propagates through the thundercloud with an intensive electric field by using the modified EGS5. The region of the intensive electric field supposed

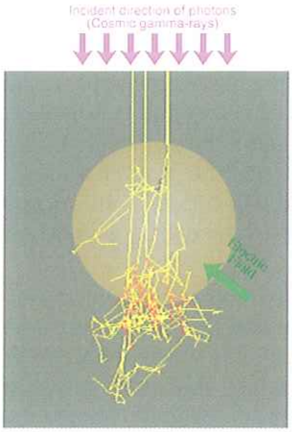

Fig. 3 (a) A calculation model for Monte Carlo simulation. Negatively charged spherical region (dark yellow) with 500 m radius is given. Some of trajectories of positron (blue), electrons (red) and photons (yellow) given by the modified EGS5 code are shown.

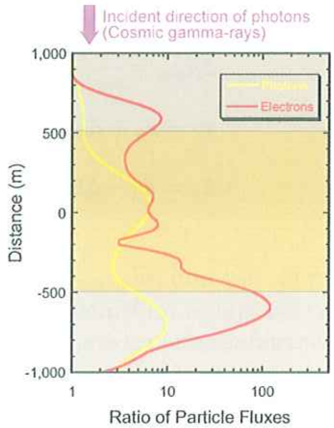

Fig. 3 (b) The ratio of particle fluxes calculated with Monte Carlo simulation when the cosmic gamma rays (photons) are injected at 1000 m from up to down and propagate through the negatively charged spherical region (dark yellow).

here is a sphere with the radius of 500 m in which negative charges are uniformly distributed, and the maximum electric field E_{max} at the surface of the sphere is assumed to be −300 and −400 kV/m. From Fig. 2, one can recognize that the calculated energy spectrum coincides with the observed one when assuming that the electric field on the surface is −400kV/m. In the case of this model, the generated photon flux becomes the maximum at about 200 m outside the region of negative electric charge when the surface intensity is −400 kV/m, because secondary electrons generated by incident photon flux are accelerated outside around the region (Fig. 3).

Here, we discuss the generation altitude and process of the TER. If high-energy charged particles such as secondary cosmic rays pass through a negatively charged region inside the thundercloud, the increasing rate of the radiation flux becomes large at a few hundreds of meters outside the charged region, because the electromagnetic shower still continues outside the region. From the observed spectrum and the calculation, the TER is the bremsstrahlung photons from the runaway electrons. The characteristic length for the runaway breakdown is not sufficiently obtained in our model. In other words, the runaway breakdown is not archived. In fact, the lightning discharge was not observed in this event.

4. Conclusion.

By means of Monte Carlo simulation, we calculate the radiation intensity and spectrum to verify the observed energetic radiation, lasting for several minutes. When the electric field intensity on the surface of spherical negatively charged region is −400 kV/m, the calculation agrees with the observation. From the calculation, the maximum intensity appears 200 meter beneath the bottom of the negatively charged region. Our results are also consistent with the evidence of no CG discharge.

Acknowledgements. We thank Mr. Yasuyuki Watanabe and Mr. Sho Katakura (Tokyo Gakugei University) for their assistance of this work. This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (B), No. 24360399, 2012 (T. T. and M. K.).

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(Received February 25, 2013; revised July 5, 2013; accepted September 1, 2013)