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Multiple Gamma-ray Glows and a Downward TGF Observed from Nearby Thunderclouds

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Key Points:

- Four gamma-ray enhancements were observed at two locations 1.35 km apart along the wind direction, and their time profiles were analyzed.
- Termination of three of them was also recorded. The last one was associated with a downward TGF and a negative energetic in-cloud pulse.
- The acceleration region of gamma-ray glows in a thundercloud can develop within a few minutes after experiencing a discharge.

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Abstract

Around 17:00 on January 12, 2020 (UTC), radiation detectors installed at two locations with a 1.35 km separation in Kanazawa City, Japan, captured a total of four gamma-ray enhancements. The first pair was simultaneously observed at the two locations at 17:03, and were abruptly terminated by a lightning discharge. The remaining two enhancements were also nearly simultaneously observed ∼3 minutes later, and one of them was also terminated by another lightning discharge. At the last termination, a downward TGF and a negative energetic in-cloud pulse were observed. Both pairs were associated with thundercloud cells. In the first pair, simultaneous detection in two locations 1.35 km apart suggests either a gamma-ray glow emerged in-between and time variability of its intensity were directly observed, or there were two (or more) gamma-ray glows in the cell which reached the two detectors coincidentally. In the latter pair, the peak time in the downwind detector was ∼40 s later than that of the upwind detector. If the irradiation region moved with the cell, it would have taken ∼ 110 s. The discrepancy suggests either the glow moved 2.5 times faster than the cell, or there were two (or more) glows in the cell. Also, the fact that the thunderstorm cell hosting the latter glows experienced the lightning discharge ∼3 minutes before suggests that the strong electric field in the cell can develop within a few minutes.

Plain Language Summary

Thunderclouds sometime emit gamma rays with a duration of minutes, which are called "gamma-ray glow". It is bremsstrahlung emission from high-energy electrons accelerated in the cloud. At around 17:00 (UTC) January 12, 2020, two radiation detectors installed 1.35 km apart in Kanazawa City, Japan, captured a total of four count rate enhancements. The first two disappeared with a lightning discharge, and the last one with another lightning, in this case accompanied by an intense gamma ray flash called a "downward terrestrial gamma-ray flash" (TGF). The overall behavior is similar to another gamma-ray glow observed in the same location on January 2018 (e.g. Wada, Enoto, Nakamura, et al., 2019). This is also the third report of gamma-ray glow termination associated with both lightning discharges and TGFs. However, while the 2018 event can be explained well by assuming that the electron acceleration region moves with the thundercloud cell (monitored by rainfall map) and then terminated by a lightning discharge, the time profiles of the four current events cannot. To explain the behavior of the 2020 data, new models such as electron acceleration region(s) rapidly emerging in a thundercloud cell, and/or multiple electron acceleration regions co-existing in a single cell, are discussed.

1 Introduction

Parks et al. (1981b) and McCarthy and Parks (1985a) captured a phenomenon of X-ray intensification during a passage of a thundercloud using an aircraft-mounted X-ray detector for the first time. Balloon experiments by Eack et al. (1996) observed similar X-ray emissions. These observations were followed by further aircraft (e.g. Kelley et al. (2015); Østgaard et al. (2019); Kochkin et al. (2017, 2021)), balloon (Eack et al., 2000), and ground-based observations (e.g. Torii et al. (2002); Chilingarian et al. (2010); Tsuchiya et al. (2007)), which detected not only X-rays but also gamma rays up to tens of MeV. These X- and gamma-ray flux intensifications have a duration ranging from tens of seconds to minutes, are associated with thunderclouds themselves, not with lightning discharges, and are now called "gamma-ray glows" (e.g. Kuroda et al., 2016; Wada, Enoto, Nakamura, et al., 2019), long bursts (e.g. Torii et al., 2009), and/or thunderstorm ground enhancements (Chilingarian et al., 2011). Besides gamma-ray glows, in 1990s, the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory detected gamma-ray emissions with a duration of a few milliseconds arriving from the ground (Fishman et al., 1994). They are now called "terrestrial gamma-ray flashes" (TGFs) and are known to be synchronized with lightning discharges. Their average spectra have continuous shape up to > 10 MeV, and is now considered as the bremsstrahlung emission from electrons accelerated mainly via the relativistic runaway electron avalanche (RREA) mechanism (Gurevich et al., 1992). Spectra of gamma-ray glows are similar to those of the TGFs (e.g. Tsuchiya et al., 2007; Dwyer, 2012; Kochkin et al., 2021), and therefore the RREA mechanism is also considered to be applicable to it. However, intensity of some of the brightest glows cannot be explained solely by this mechanism (Kelley et al., 2015; Wada, Enoto, Nakamura, et al., 2019), and a further amplification process such as relativistic feedback (Dwyer, 2003, 2012) is needed.

The region along the Sea of Japan is famous for its winter thunderstorms. Low-altitude cloud bases of winter thunderstorms (typically 0.2–0.8 km, Goto and Narita (1992)) make the region a good place for ground-based observations of gamma-ray glows and downward TGFs, as gamma rays are less likely to be attenuated compared to summer thunderstorms with high-altitude charge-center, before reaching the ground. We have conducted the Gamma-Ray Observation of Winter Thunderclouds (GROWTH) experiment in this region since 2006 (e.g. Tsuchiya et al., 2007; Yuasa et al., 2020), and continuously observed gamma-ray enhancements of tens of seconds, which are thought to be originating from gamma-ray glows (e.g Tsuchiya et al., 2011, 2013; Wada et al., 2018). In addition, < 1 ms short-duration on-ground radiation flashes coincident with lightning discharges, which can be interpreted as TGFs aiming at the ground (or "downward TGFs"), have been detected. They are also sometimes associated with emission with a duration of a few hundred milliseconds (called "short bursts") (Enoto et al., 2017; Bowers et al., 2017; Wada, Enoto, Nakazawa, et al., 2019). Enoto et al. (2017) and Bowers et al. (2017) revealed that TGF photons produce neutrons via photonuclear reactions with atmospheric neuclei, and the short bursts originate from de-excitation gamma rays of neutron captures generated through the reaction.

Association with lightning discharge is confirmed in all downward TGFs reported in this region (Enoto et al., 2017; Bowers et al., 2017; Wada, Enoto, Nakazawa, et al., 2019; Wada, Enoto, Nakamura, et al., 2020, 2019). This fact make them distinct from the fare weather Extensive Air Shower (EAS) events recorded in high-altitude cosmic ray observatories (e.g. Bowers et al., 2021). In some downward TGF cases, a characteristic bipolar radio waveform with high peak currents (>100 kA) called an "energetic in-cloud pulse" (EIP) has been observed in the low frequency radio band (0.8–500 kHz, Wada, Enoto, Nakamura, et al., 2020). EIP has also been observed coincident with TGFs detected by in-orbit satellites, and is likely to be related to at least some of the origins of TGFs (Lyu et al., 2015; Østgaard et al., 2021).

One of the mysteries on gamma-ray glows is that they last for more than a few minutes. Strong electric fields accelerating electrons are considered to exist in thunderclouds. According to the RREA process, even small changes in electric-field strength can vary multiplication factor of electrons by orders of magnitudes (e.g. Dwyer and Smith (2005)). Nonetheless, gamma-ray glows seem to have a stable photon flux and move with ambient wind (e.g. Torii et al., 2011). We have installed more than ten gamma-ray detectors at 1-3 km intervals on the ground and have observed an increase and decrease in gamma rays as thunderclouds are swept away by the wind. Since the size of the irradiated region of the glows is typically a few hundred meters (Wada, Enoto, Nakamura, et al., 2019), a gamma-ray glow can be seen by a single detector only for a few tens of seconds with a typical wind velocity of 10–20 m s^{-1}. Therefore, it is difficult to follow the time evolution of gamma-ray glows with a single detector.

Terminations of gamma-ray glows synchronously with lightning discharges have often been observed (e.g. Chilingarian et al., 2017; McCarthy & Parks, 1985b; Parks et al., 1981a; Eack et al., 1996; Eack & Beasley, 2015). One of these was detected by Wada, Enoto, Nakamura, et al. (2019, 2020) in January 2018. A gamma-ray glow following the wind moved over two detectors 1.35 km apart, and a lightning discharge caused the glow to cease in the vicinity of the downwind detector. They confirmed that the glow was disrupted coincident with a downward TGF and an EIP. Association of TGF and glow is also suggested by Smith et al. (2018) in another location near Kanazawa city.

In this paper, we report gamma-ray glows observed in January 2020 at the same location as Wada, Enoto, Nakamura, et al. (2019). While apparently similar to the January 2018 event, this event in January 2020 is characterized by a more complex temporal variability.

2 Observation & Methods

From 2006, our GROWTH gamma-ray detectors were deployed at the Kashiwazaki-Kariwa Nuclear Power Station in Niigata Prefecture, and gamma-ray glows were observed (Tsuchiya et al., 2007, 2011, 2013). In 2015, we established another observation site in Kanazawa city, Ishikawa Prefecture, and started the multiple-point observation campaign. One of the main objectives is to investigate the time evolution of gamma-ray glows, which is thought to move with thunderclouds (Torii et al., 2011). In the 2019–2020 winter season, 20 detectors were deployed in this area.

The detectors used in this study are the same as the ones used in Wada, Enoto, Nakamura, et al. (2019). Each detector has a $25\times8\times2.5$ cm^3 $Bi_4Ge_3O_{12}$ scintillator read out with two photo-multiplier tubes (PMTs). Analog output is converted into digital signals with 50-MHz sampling and processed by a field programmable gate array to obtain pulse height of each photon signal. The detectors record the pulse height and trigger time. It also records the minimum voltage value of the waveform to check analog circuit anomaly such as undershooting due to a large signal (Yuasa et al., 2020). Both of the detectors in the present paper are sensitive to the energy range of 0.4–20.0 MeV. Detector A is installed at Izumigaoka High School (36.538°N, 136.649°E) and Detector B at Kanazawa University High School (36.539°N, 136.664°E).

S=0.02 m.sq.

Broadband low-frequency (LF: 0.8–500 kHz) radio receivers have been deployed in the area to monitor lightning activities there (Takayanagi et al., 2013). Each station has a flat plate antenna and their analogue outputs are sampled by a 4 MHz digitizer. Timing is calibrated with the GPS signals. The locations of the 7 stations that make up the array are shown in Supplementary Figure 3a of Wada, Enoto, Nakamura, et al. (2019). Pulse locations are obtained by the time-of-arrival method with the multiple LF antennae (Yoshida et al., 2014). Lightning data obtained by Japanese Lightning Detection Network (JLDN) operated by Franklin Japan, were also used. JLDN provides the location, peak current, and timing of lightning discharges.

In order to study structure of thunderclouds during gamma-ray glows, we utilize data of the eXtended RAdar Information Network (XRAIN) operated by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). XRAIN is a dual-polarized radar network in the X-band (9.8 GHz), which measures the shape of raindrops and/or hails from the reflection intensity, and estimates the rainfall intensity in the observation area. In the analysis, we use the 1-minute-interval synthetic rainfall data obtained from the Nomi XRAIN radar site, located 18 km southwest from Detector A. It is synthesized using the scan of 1.7° and 3.6° elevation angles, which corresponds to $\sim$ 530 m and $\sim$ 1.1 km altitude around our gamma-ray detectors, respectively.

3 Data Analysis

3.1 Detection of four enhancements in gamma-ray count rates

Shortly after 17:00, January 12, 2020 (UTC, or 02:00 on January 13, JST; hereafter, all time information is in UTC), we observed a total of four count-rate enhancements with Detectors A and B.

We use the XRAIN synthetic rainfall contours to determine the wind direction and speed by tracking the movement of the thundercloud cells near the detectors around the event detection time. The estimated wind direction and speed are 246° (clockwise with respect to north: wind from west-southwest toward east-northeast) and 14.2 ± 1.2 m s^{-1}, respectively. Therefore Detector A was located almost upwind of Detector B. See Appendix A for detail.

Figure 1 shows the time variation of count rates recorded by Detectors A and B in the energy band of 3–20 MeV. This energy band in not affected by the radon-decay-chain nulcei variable with precipitation. At around 17:03 and 17:05–17:07, each of the detectors captured two gamma-ray count-rate enhancements: A1 and A2 by Detector A and B1 and B2 by Detector B. Here we define $t = 0$ s at 17:06:59, and the "enhancement" when the count rate is continuously exceeding 12 counts s^{-1}, which corresponds to $\sim 2\ \sigma$ above the background count rate of ~ 6.6 counts s^{-1}. The A1 and B1 events started to rise at around 17:02:50 ($t = -250$ s) and 17:03:03 ($t = -237$ s), respectively, brightened by $\sim$30 s, and then suddenly terminated at 17:03:23 ($t = -215$ s). The A1 and B1 events seemed to be simultaneously initiated and terminated at a distance of 1.35 km (the distance between Detectors A and B). The A2 event occurred from 17:04:54 ($t = -125$ s) to 17:06:09 ($t = -50$ s) with a duration of $\sim$70 s. The B2 event started at 17:05:19 ($t = -100$ s) and continued for $\sim$100 s, and then terminated at 17:06:59 ($t = 0$ s). The peak time of B2 is 17:06:09 ($t = -50$ s), which is $\sim$40 s after the peak time of A2. In Figure 1, the discharges coincident with the interruption of the A1/B1 event and the B2 event are named the L1 discharge and L2 discharge, respectively. Energy spectra of the four enhancements are typical of those observed and reported by the GROWTH experiment, which were well explained by bremsstrahlung gamma rays from electrons generated via RREA process (e.g. Wada, Enoto, Nakamura, et al., 2019).

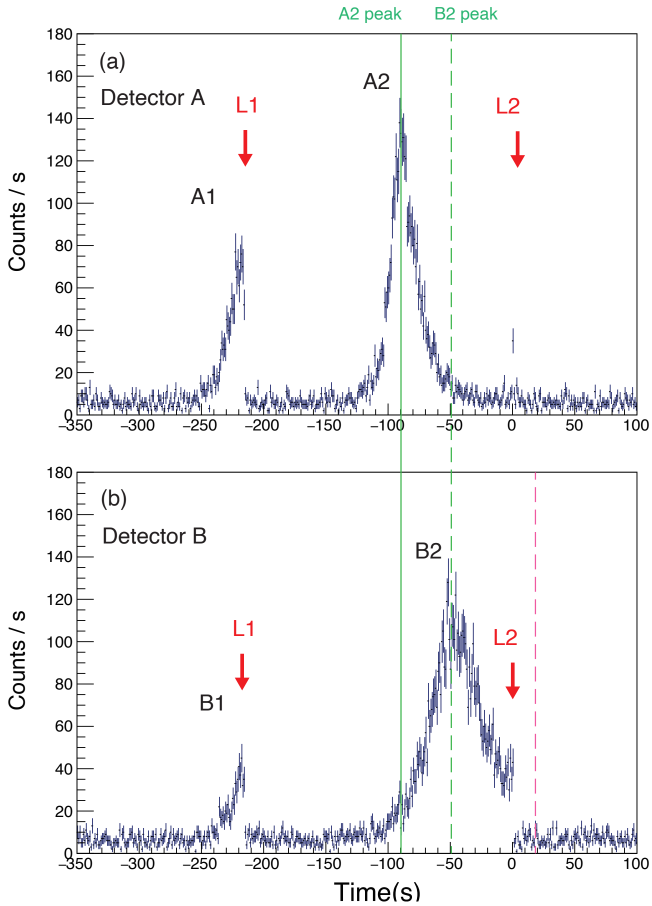

Figure 1. The upper and lower panels show the 1-sec-binned time variation of count rates of Detectors A and B, respectively, in the energy range of 3–20 MeV. Error-bars are for $\pm$ 1 σ, throughout this paper. The time origin is the moment of the TGF coincident with the L2 discharge. The red arrows indicate the time of the lightning discharges L1 and L2, the solid and dotted green lines the peak positions of A2 and B2 events respectively, and the dashed magenta line shows the expected peak time at Detector B, assuming that the irradiation area of A2 moves with thundercloud cell.

We analyzed the synthesized rainfall map obtained by XRAIN. Like many other gamma-ray glows observed in the region (e.g. Torii et al. (2011); Wada, Enoto, Nakamura, et al. (2019); Wada et al. (2021)), the gamma-ray enhancements were observed when the heavy rain region is located near the detectors. The rainfall distribution at 17:02–17:03, which includes the time when the A1 and B1 enhancement events occurred, are shown on the left panel of Figure 2. There are two regions with rainfall exceeding $\sim$ 15 mm h^{-1}. We identify them as "thundercloud cells". One with a size of $\sim$ 4 km diameter was located around the detectors (named Cell-1), and another larger one to the southwest (Cell-2). Detectors A and B were beneath the east-west elongated heavy rain peak area of Cell-1. The map at 17:06–17:07 corresponding to the A2 and B2 enhancement events is also shown on the right panel of Figure 2. Cell-2 has moved near Detectors A and B at this moment. Although the rain activity is a little decreased, both detectors are still under strong rain exceeding $\sim$ 15 mm h^{-1}.

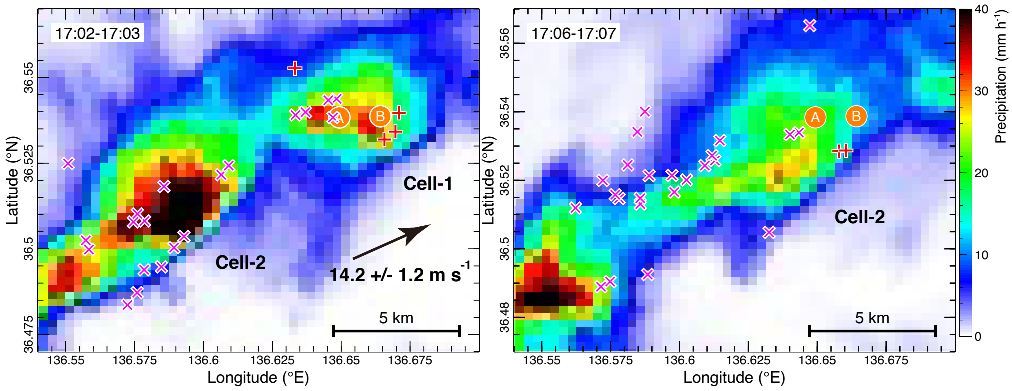

Figure 2. Two-dimensional view of one-minute rainfall contour map by XRAIN rainfall radar at 17:02–17:03 (corresponding to $-298 < t < -238$ s) and 17:06–17:07 (corresponding to $-59 < t < 1$ s). Both are synthesized from the 1.7° scans. Overlaid red-plus and magenta-cross marks are the positions of lightning discharges identified by JLDN and the LF network (see text for detail), respectively. Those in the 17:02–17:03 panel corresponds to the timing of the L1 discharge, while those in 17:06–17:07 panel corresponds to the L2 discharge.
Typical localization error of JLDN is reported to be 310 m (Matsui et al., 2020). The orange markers show the position of the radiation detectors A and B.

3.2 Downward TGF and short burst

At the time of the B2 event termination, both Detectors A and B recorded a downward TGF followed by a ~ 100 ms decaying emission (or "short burst"). Figure 3 left shows time series of the maximum (black dots) and minimum (red dots) voltages of photon event waveform. There are a few photon events recorded with maximum voltage of $\sim$4.7 V at $t = 0$ s, which is at the saturation level of the analog circuit. Immediately after that, the analog circuit experiences a significant undershoot for a few milliseconds. These are signatures of a large number of gamma-ray photons coming in a short period, as reproduced well by LED irradiation experiments using the same PMT and analog circuit (see section 4.2.4 and Figure 4.19 of Wada (2021)), and hence evidence of a downward TGF (see Enoto et al., 2017). Figure 3 right shows the time variation in count rates with the 10-ms bin. The time variations characterized by fast rise and exponential decay are observed in both detectors.

The count rates decay and disappear within ~ 100 ms. Its overall behavior resembles those of the simulated TGF-originated neutron signals as shown in Figure 5 of Bowers et al. (2017) and Figure 9 of Wada, Enoto, Nakazawa, Odaka, et al. (2020a). Therefore, the time variations of count rates can be interpreted as gamma rays originating from neutrons generated by photonuclear reactions (Enoto et al., 2017; Wada, Enoto, Nakazawa, Odaka, et al., 2020b; Wada, Enoto, Nakazawa, Yuasa, et al., 2020). The B2 event was terminated with the occurrence of the downward TGF. This is the third case of the simultaneous detection of glow-termination and a downward TGF, following those reported by Smith et al. (2018) and Wada, Enoto, Nakamura, et al. (2019). At the timing of L1, none of our detector recorded a strong signal.

At the termination of the A1 and B1 events, JLDN detected four radio pulses of a lightning flash (L1) in 200 ms, as summarized in Table 1. Since they occurred within a radius of 4 km from both detectors with peak current of negative 5–12 kA, they are considered to be the cause of the termination of A1 and B1 events. Also, when the B2

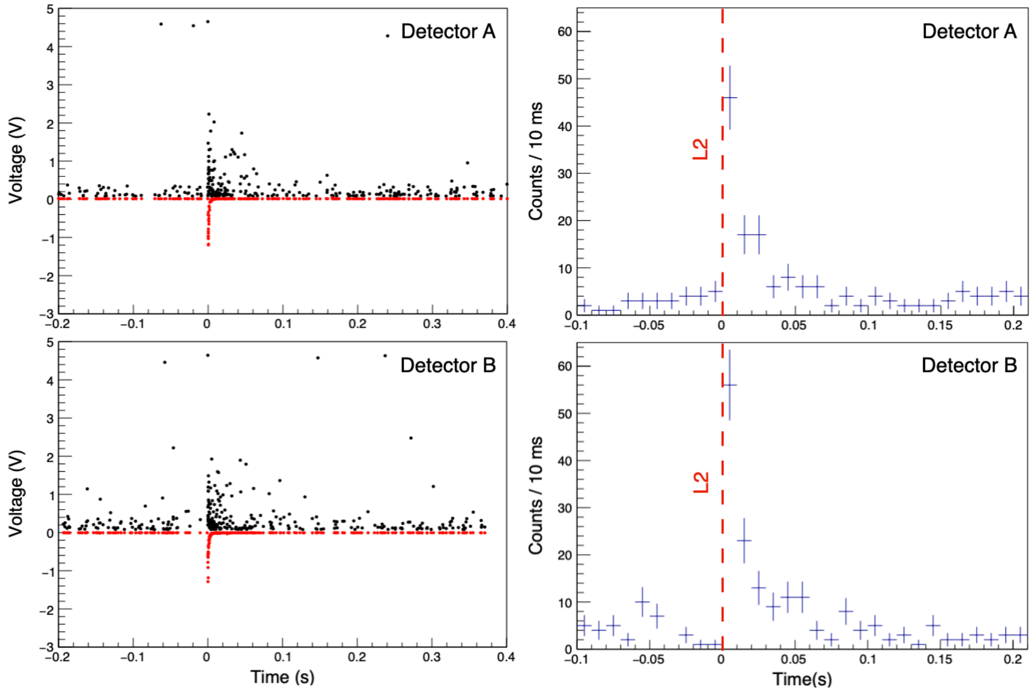

Figure 3. Diagram of the downward TGF and the photonuclear reactions coincident with the L2 discharge. Black and red dots in the left panel show time series of the maximum and minimum values of photon-event waveforms at the moment of the L2 discharge, respectively. The right panel presents 10-ms-binned count-rate histories. The time origin is set to be the detection time of the downward TGF coincident with the L2 discharge.

event was terminated and a downward TGF occurred, JLDN detected two radio pulses of another lightning flash (L2), both located within 2 km from the two detectors. The first radio pulse (JLDN pulse 8) coincided with the downward TGF recorded by Detectors A within $\sim 5\ \mu$s. GPS of Detector B was locked-off at the moment, and we can just state that its timing is consistent with the pulse within $\sim 100\ \mu$s uncertainty. According to the JLDN report, JLDN pulse 8 had a large negative peak current of 122 kA.

Table 1. JLDN reported discharge information.

Pulse ID	Time (UTC)	Location	Peak current	note
1	17:01:22.16521	(36.530°N, 136.622°E)	−13 kA	
2	17:01:22.18520	(36.541°N, 136.626°E)	22 kA	
3	17:01:22.31134	(36.540°N, 136.627°E)	19 kA	
4	17:03:23.80842	(36.540°N, 136.671°E)	−12 kA	L1
5	17:03:23.81123	(36.553°N, 136.633°E)	−10 kA	L1
6	17:03:23.83458	(36.532°N, 136.666°E)	−5 kA	L1
7	17:03:24.00174	(36.534°N, 136.670°E)	−12 kA	L1
8	17:06:59.05044	(36.529°N, 136.658°E)	−122 kA	L2
9	17:06:59.05598	(36.529°N, 136.660°E)	9 kA	L2

Figure 4 shows radio-frequency waveforms of the lightning discharges recorded by the broadband LF observation network. The data was recorded by one of our LF antennae, installed in Himi City, Toyama Prefecture, Japan (36.938°N, 137.025°E). The top panel of Figure 4 covers the duration of the L1 lightning flash. Pulse identification by JLDN is also shown. The middle panel covers those of the L2 flash, and the bottom one gives the enlarged view of the LF waveform corresponding to JLDN pulse 8 . The waveform in the last panel has a similar characteristics as the radio pulse coincident with the downward TGF reported by Wada, Enoto, Nakamura, et al. (2020) and its peak current reported by JLDN is larger than negative 100 kA. Based on the definition of Lyu et al. (2015), the pulse duration was estimated to be 85 μs. Since the LF pulse has a longer duration than that of typical narrow bipolar events and is isolated from other LF activities, it can be classified as a negative EIP. Close up of the LF waveform of the timing corresponding to all the six JLDN pulses included in L1 and L2 are shown in Appendix B.

Figure 2 shows the location of the LF radio pulses in the lightning flashes L1 and L2. For both L1 and L2, the LF pulses are located in the thundercloud cells corresponding to the A1/B1 (Cell-1) and A2/B2 events (Cell-2) , respectively. No lightning discharges were recorded by JLDN and the LF networks for the 3.5 minutes between L1 and L2.

4 Discussion

Here we discuss the possible geometries of the gamma-ray glows causing the gamma-ray count-rate enhancements. The A1 and B1 enhancement events were terminated by the L1 discharge. Since Detectors A and B are 1.35 km apart, there are two possibilities for simultaneous enhancement detection at two sites. One is that there is a single gamma-ray glow that is so wide that it covers two detectors 1.35 km apart at the same time. Previous observations of gamma-ray glows during winter thunderstorms in Japan suggested that gamma-ray glows are moving with thunderclouds (precisely, with rainfall regions; see Wada, Enoto, Nakamura, et al. (2019); Yuasa et al. (2020); Torii et al. (2011)). However, in the present case, since the ambient wind is heading from Detector A to B, Detector A should observe the gamma-ray enhancement $\sim$110 s earlier than Detector B, if the gamma-ray glow has small variance of the flux in time. This does not

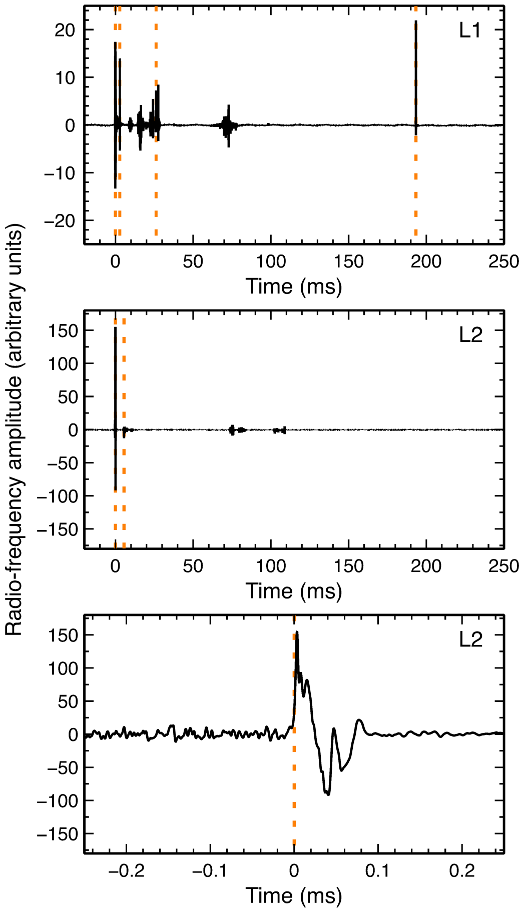

Figure 4. LF waveforms captured by the Himi station at the time of the lightning discharges. The top and middle panels present the 250 ms long overall waveform of L1 and L2, respectively. The orange dotted lines represent the timing of the JLDN pulses. The time origin of the top panel is the JLDN pulse 4 , and that of the other two panels is JLDN pulse 8 . The bottom panel presents the close-up (0.5 ms wide) view for the LF pulse corresponding to JLDN pulse 8 . The propagation delay between the LF station and the lightning location ($\sim$ 55 km) is 0.18 ms and corrected in this figure.

match the observation results. To explain the simultaneous emergence of the A1 and B1 events in Detectors A and B, one idea is to assume that acceleration region just started building up at around $t = -250$ s, and the quick rise of the gamma-ray count rates are mainly the result of the increase in its intensity, rather than the gamma-ray glow movement with the thundercloud cell. If the accelerator was located in-between Detectors A and B, its size will be ~ 1 km wide, which is not much different from that of the known typical gamma-ray glows in this region.

At Aragats it can bi 10km

The other possibility is that two (or more) acceleration regions, namely multiple gamma-ray glows, existed independently near Detectors A and B at the same time. As shown in Figure 2, at 17:02–17:03 (close to the time when the A1 and B1 events occur), the peak of the heavy rain region is elongated east-west in Cell-1. The two (or more) acceleration regions placed in its western and eastern ends, which are actually slightly peaked, will be able to explain the two enhancements. With the lightning L1 with four negative current pulses, the electric field within Cell-1 overall could have been decreased significantly. If the electric field becomes less than the RREA threshold value ~ 285 kV m^{-1} (e.g. Dwyer, 2012), electron acceleration ceases. Therefore, a discharge can halt the two (or more) acceleration regions at the same time.

they don't understand what glow is! it is not one global proces over km.sq, but multiple avalanches!

Regarding the A2 and B2 enhancements, the peak timing of B2 is about 40 s after that of A2. The distance between the two detectors is 1.35 km and the azimuth angle of Detector A seen from Detector B is 275° (clockwise from the north), only 29° offset clockwise from the wind direction. Using the wind speed and direction estimated by XRAIN, the peak of the B2 event is expected to come 109±10 s after the peak of the A2 event if originating from an identical gamma-ray glow moving along with Cell-2. This estimated peak time is shown by the magenta dotted line in Figure 1. However, the actual peak time is about 40 s after the peak time of A2 as shown by the green dotted line, which is inconsistent under the assumption. One possibility is that the acceleration region was moving 2.5 times faster than the overall thundercloud, an idea that is very new and needs detailed investigation in future. Another possible scenario is that, in addition to the acceleration region causing A2, another acceleration region existed (or suddenly emerged) in the thundercloud Cell-2, and caused the B2 enhancement. The first one disappeared with discharge L2, before reaching near Detector B. The third scenario is a complex-shaped gamma-ray irradiation area, which may have passed over two detectors in sequence. In fact, this scenario is not much different from the second one assuming multiple acceleration regions. To unambiguously distinguish among these models, more detectors are needed to be located in between Detectors A and B.

Cloud is moving, but electric field in moving cloud will be changed!

Acceleration region is large!

Wada, Enoto, Nakamura, et al. (2019) reported that the gamma-ray glow observed in the same location on 9 Janauary, 2018, can be well explained by the picture that it moved along with a thundercloud cell, passed over Detector A on the upwind, and disappeared with a lightning discharge when located above Detector B. In addition, by an observation with 10 detectors, Torii et al. (2011) also explained another glow with the picture that its irradiation area moved along with the wind while roughly maintaining its shape and size. Therefore, gamma-ray glows reported in this paper are clearly distinct from those results, indicating that either there is a case that the acceleration region does not follow the thundercloud cells' movement, or the glow intensity can increase as fast as ~ 30 seconds, and/or multiple acceleration regions exist and/or emerge in a single thundercloud cell.

As in Figure 1, at the moment of the A1 and B1 termination, LF pulses were detected in the thundercloud Cell-1 as well as Cell-2. Wada et al. (2018) observed that discharges (observed as LF pulses) passing right above the gamma-ray detector located at Suzu region have terminated the corresponding gamma-ray glow. In the same way, electric fields in Cell-2 can be significantly reduced by the L1 discharge. However, Cell-2 hosted the A2/B2 events 3 minutes after the A1/B1 termination and the L1 discharges, and then resulted in the L2 discharges. Therefore, it is suggested that the electric field of Cell-2 should have been regained rapidly within 3 minutes.

5 Conclusion

Analysis of four gamma-ray enhancements detected by two detectors in Kanazawa city on January 12, 2020, suggested that there are either electron acceleration regions which suddenly emerge with ~ 30 s timescale, regions not moving along with thundercloud cells, or the existence of multiple adjacent acceleration regions within a single thundercloud cell. The observation result is different from the picture that a single electron acceleration region was moving along with thundercloud cell, as previously reported by Torii et al. (2011), Wada, Enoto, Nakamura, et al. (2019) and Yuasa et al. (2020). The gamma-ray glows were terminated by lightning discharges, one of which coincided with a downward TGF associated with an LF radio waveform typical of negative EIP. It is also suggested that the electron acceleration region revives quickly after the lightning discharge within ~ 3 minutes.

Appendix A XRAIN precipitation radar images and wind direction/speed estimation

In Figure A1, precipitation maps obtained by XRAIN in one-minute intervals are presented for 10 minutes duration. Original data can be obtained from DIAS service (https://diasjp.net, which was then supported by the University of Tokyo, and from April 2021, by JAMSTEC). Applying the method presented in the “Wind estimation with X-band radar” section of “Method” in Wada, Enoto, Nakamura, et al. (2019) to this precipitation images, we determined the wind direction and speed as 246° (clockwise with respect to north) and 14.2 ± 1.2 m s^{-1}, respectively. The wind was blowing from west-southwest, and Detector A was located almost upwind of Detector B. In the figures, nine lightning discharge locations from JLDN recorded within this 10 minutes (see Table 1) are also plotted (while those of the LF arrays are not shown for simplicity).

Appendix B Close up views of LF waveform

In Figure B1, we present the close up LF waveforms of the six pulses recorded at the Himi station, corresponding to the timing of four and two JLDN pulses included in the L1 and L2 flashes, respectively.

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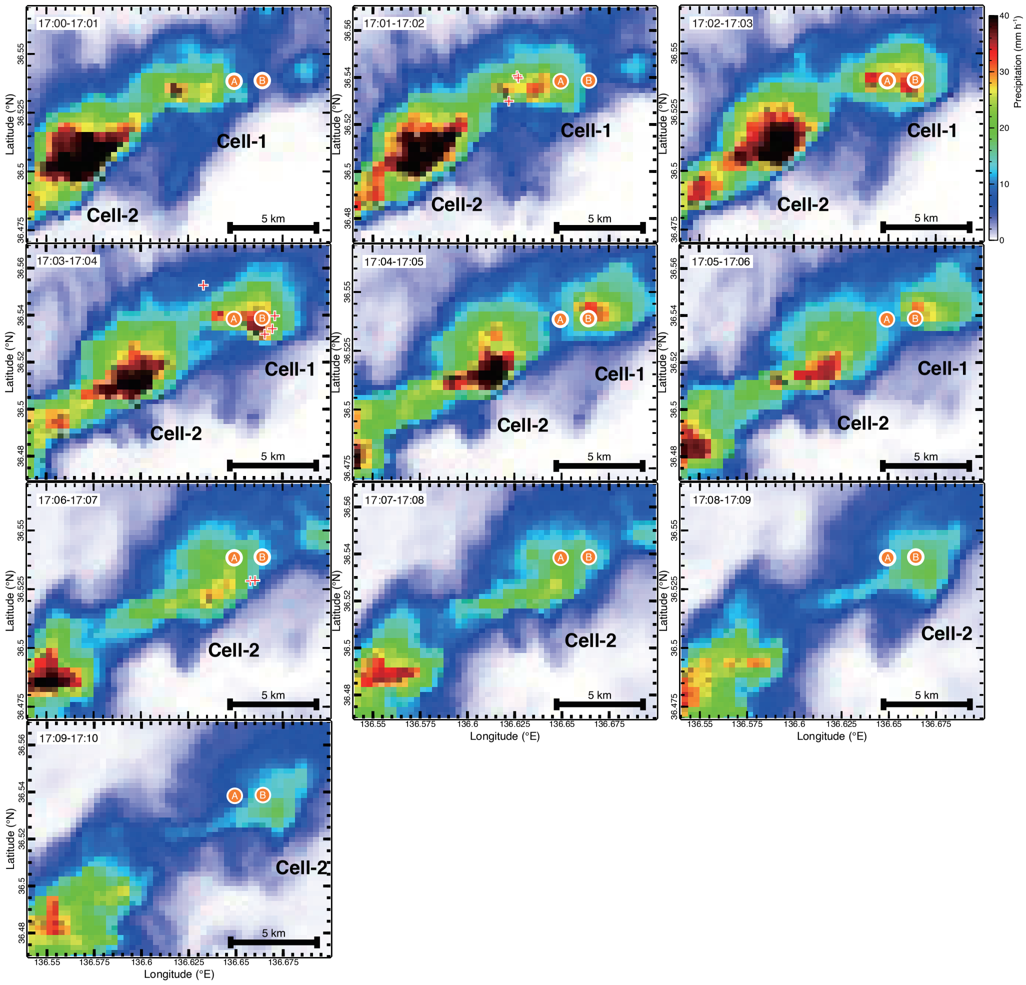

Figure A1. Two-dimensional view of one-minute rainfall contour map by XRAIN rainfall radar at 17:00–17:10. The format is the same as Figure 2. Panels with the odd end time are synthesized from the 1.7° scans, while those with even time are from the 3.6° scans. The red plus-marks represent the position of the nine lightning discharges identified by JLDN; three around 17:01:22, four around 17:03:23-24, and two around 17:06:59.

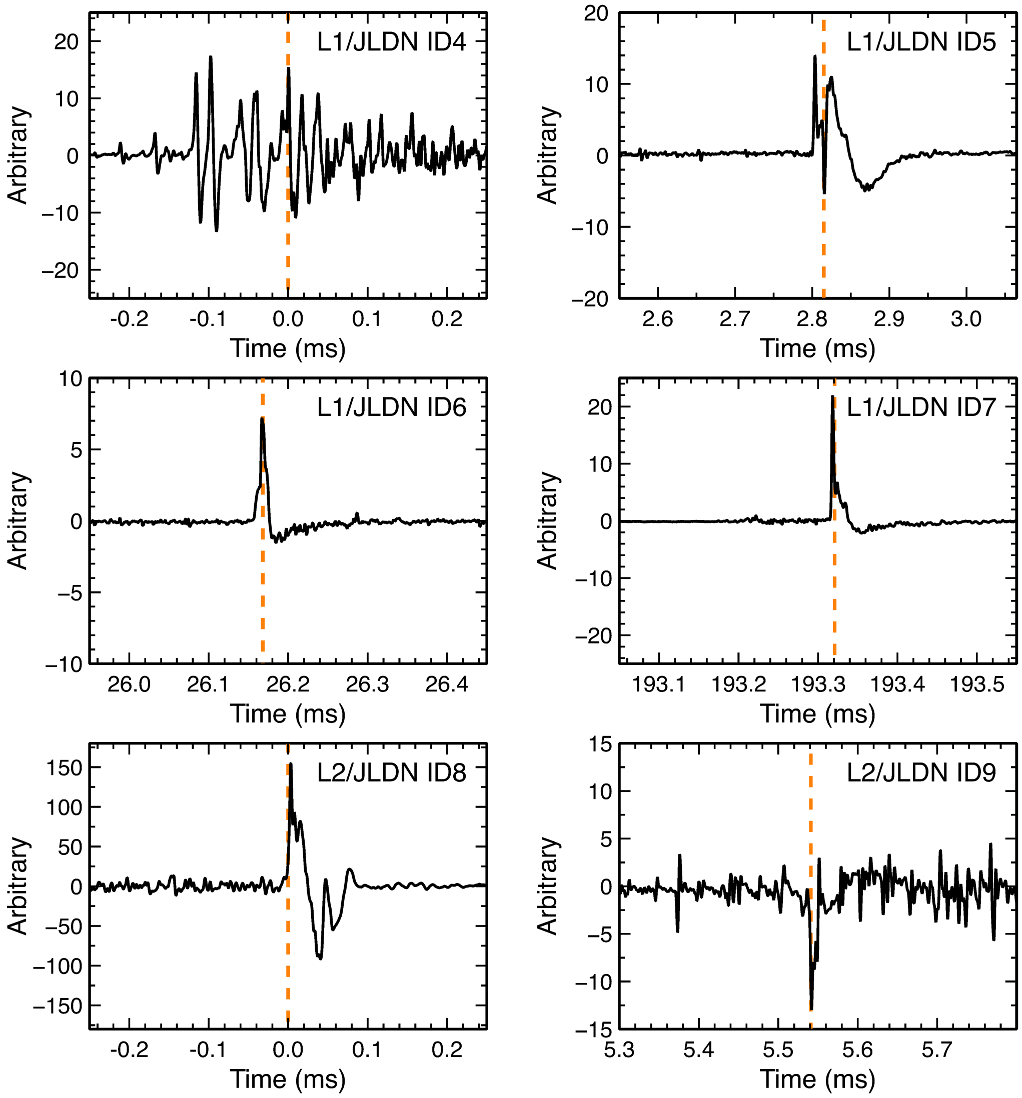

Figure B1. Enlarged LF waveform of JLDN pulses 4 to 9, obtained by the station located in Himi City. The time origin is the moment of JLDN pulse 4 and JLDN pulse 8 for the L1 and L2 flashes, respectively.

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