Citizen science observation of a gamma-ray glow associated with the initiation of a lightning flash

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Abstract

Gamma-ray glows are observational evidence of relativistic electron acceleration due to the electric field in thunderclouds. However, it is yet to be understood whether such relativistic electrons contribute to the initiation of lightning discharges. To tackle this question, we started the citizen science “Thundercloud Project’, where we map radiation measurements of glows from winter thunderclouds along Japan sea coast area. We developed and deployed 58 compact gamma-ray monitors at the end of 2021. On 30 December 2021, five monitors simultaneously detected a glow with its radiation distribution horizontally extending for 2 km.

The glow terminated coinciding with a lightning flash at 04:08:34 JST, which was recorded by the two radio-band lightning mapping systems, FALMA and DALMA. The initial discharges during the preliminary breakdown started above the glow, i.e., in vicinity of the electron acceleration site. This result provides one example of possible connections between electron acceleration and lightning initiation.

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Key Points:

- We started the citizen science “Thundercloud Project”, a multi-point observation campaign of gamma-ray glows from thunderstorms.
- On 30 December 2021, five radiation monitors detected a 2-km-long size gamma-ray glow, which suddenly terminated with a lightning flash.
- Two radio mapping systems of lightning identified the initiation of the discharges, which started at a location above the glow region.

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Abstract

Gamma-ray glows are observational evidence of relativistic electron acceleration due to the electric field in thunderclouds. However, it is yet to be understood whether such relativistic electrons contribute to the initiation of lightning discharges. To tackle this question, we started the citizen science "Thundercloud Project", where we map radiation measurements of glows from winter thunderclouds along Japan sea coast area. We developed and deployed 58 compact gamma-ray monitors at the end of 2021. On 30 December 2021, five monitors simultaneously detected a glow with its radiation distribution horizontally extending for 2 km. The glow terminated coinciding with a lightning flash at 04:08:34 JST, which was recorded by the two radio-band lightning mapping systems, FALMA and DALMA. The initial discharges during the preliminary breakdown started above the glow, i.e., in vicinity of the electron acceleration site. This result provides one example of possible connections between electron acceleration and lightning initiation.

Plain Language Summary

Thunderstorms are natural particle accelerators. The strong electric field inside thunderclouds accelerates relativistic electrons, which emit gamma rays via interaction with the atmosphere. High-energy photons generated in this process have been observed as radiation enhancements called gamma-ray glows. Winter thunderclouds along the sea of Japan are an ideal target for monitoring glows because their altitudes are usually sufficiently low for the generated gamma-ray photons to reach the ground. We started a new citizen science "Thundercloud Project" in this area, where we distributed radiation detectors to citizen supporters to observe glows and to reveal their relationship with the aerological condition and lightning discharges. On 30 December 2021, five of those sensors detected a glow from a single thundercloud. Two of them recorded a sudden termination of the glow coinciding with a lightning flash, which was monitored by our two radio mapping systems of FALMA and DALMA. The initial discharges of the flash started at a location about 1.6 km above the glow region with an unusually fast downward progression. This paper is the first report of our citizen science project. We discuss the possibility that accelerated electrons contribute to the initiation of lightning discharges.

1 Introduction

Strong electric fields inside thunderclouds accelerate electrons up to relativistic energy and cause several types of high-energy atmospheric phenomena. One example is terrestrial gamma-ray flashes (TGFs) coinciding with lightning discharges (Smith et al., 2005; Wada et al., 2019; Enoto et al., 2017). Other phenomena "gamma-ray glows", also referred to as Thunderstorm Ground Enhancements (TGE), are radiation enhancements in the MeV range for a duration of tens of seconds to minutes during thunderstorm passages detected in ground experiments (Tsuchiya et al., 2007; Chilingarian & Sogomonyan, 2015; Wada et al., 2021).

Gamma-ray glows are thought to be bremsstrahlung from relativistic electrons accelerated through the Relativistic Runaway Electron Acceleration (RREA) process by the strong electric field (≥ 0.28 MV m^{-1}) in the thunderclouds (Dwyer, 2003; Babich et al., 2004; Gurevich et al., 1992; Kelley et al., 2015). However, many unanswered questions still remain about the characteristics, meteorological conditions, mechanism of gamma-ray glows, and their relationship with lightning discharges. In particular, it is an interesting question whether the accelerated relativistic electrons in a glow can eventually enhance the chance of lightning initiation. Observations of glow can provide a valuable indicator of the RREA electron acceleration in clouds potentially related to the initiation of lightning.

Gamma rays are attenuated in the atmosphere; the mean free path for, for example, a 10 MeV photon is about 400 m at the ground pressure (Köhn et al., 2017). Hence, ground-based measurements can detect glows from low-altitude clouds with base altitudes of not much greater than the gamma-ray mean free path. During winter in Japan, cold and dry air from the Siberia air mass frequently flows over the Tsushima warm current in the Japan Sea and brings low-altitude thunderclouds with cloud bases of 0.2–0.8 km (Goto & Narita, 1992) in the north coastal area of Japan. The area is ideal for ground observations of gamma-ray glow. We have installed an increasing number of multi-point radiation detectors in and around Kanazawa (Tsuchiya et al., 2007; Tsuchiya et al., 2013; Wada et al., 2018; Yuasa et al., 2020), which have recorded about 2 glow events per detector site per year (Wada et al., 2021).

Given that the atmospheric gamma-ray mean free path is ∼400 m, it is desirable to place detectors at intervals of a few hundred meters to track in detail the time variation of gamma rays emitted from a moving thundercloud. The observation system with this high-density grid would allow us to potentially answer several unsolved questions of high-energy atmospheric physics, including (1) the conditions for a glow to start and end, (2) the type of cloud where glows occur, e.g., size and structure of the electron-acceleration region, and (3) relationship between glows and lightning discharges. Then, we launched the new citizen science "Thundercloud Project" at Kanazawa in 2018, and present our first result of this project.

2 Methods and Observations

2.1 Citizen science "Thundercloud Project"

For the citizen science "Thundercloud Project", we newly developed a portable, easy-to-operate radiation detector named "COmpact GAmma-ray MOnitor (Cogamo)". Every winter, our project researchers send the Cogamo detectors to citizen supporters after conducting detector maintenance. Citizen supporters receive and deploy them in their houses along Japan sea coast area and join the team of radiation observations. In the Japanese fiscal year (FY) 2021, we constructed a large-scale and multi-point observation network with 58 Cogamos installed in the Ishikawa, Toyama, and Niigata prefectures. Among them, the region in and around Kanazawa city had the highest detector density with 16 radiation detectors installed in a 5 km square area. Figure 1a shows almost all Cogamo locations during the FY2021 winter campaign from December 2021 to March 2022.

The Cogamo detector is a small (23 cm × 28 cm × 10 cm) and lightweight (3 kg) radiation monitor, using a CsI (Tl) scintillator (5 cm × 5 cm × 15 cm) coupled with a Silicon Photomultipliers (SiPMs) MPPC (Multi-Pixel Photon Counter) as a photo sensor (Figure 1b). The energy range for gamma-ray spectroscopy is the ∼0.2–10 MeV band. The detector acquires the energy deposit and arrival time of each radiation event and records them into a microSD card. The time tagging is performed using GPS signals. In addition, 20-sec bin count rates in 6 energy bands for 0.2–0.5, 0.5–1, 1–2, 2–3, 3–8, and >8 MeV, GPS status, ambient temperature, humidity, and optical luminosity are recorded on the microSD card and are also sent to the web server for a quick-look purpose. An observation is started simply by connecting a GPS cable and a power cable and then turning on the power switch. Energy calibration of the Cogamo detector was performed for each file of one-hour data when analyzing, using environmental background radiation lines of ^{40}K (1.46 MeV) and ^{208}Tl (2.61 MeV).

In FY2021, we also prepared an automatic gamma-ray glow real-time alert system on our web server to remotely monitor observations. With this system, we calculate the moving average of the count rate of the specified energy bands among the 6 bands (e.g., >1 MeV). Assuming the Gaussian distribution with statistical fluctuations from the latest 20-second count rate values, we send an alert by means of posting it on Twitter when the latest count rate exceeds the predefined threshold. The project summary will be reported in subsequent papers. In FY2021 only, we also conducted optical camera and gamma-ray Compton camera imaging (Kataoka et al., 2013; Omata et al., 2020; Kuriyama et al., 2022) from a high-rise window of a hotel in Kanazawa.

2.2 XRAIN meteorological radar

To determine the movements of thunderclouds above the Cogamo detectors, we use the eXtended RAdar Information Network (XRAIN) operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. We used the data obtained with the XRAIN Nomi radar (Figure 1a), which is located 15 km away from Kanazawa in the southeast direction. The observation area is within 80 km of the radar, which covers around Kanazawa. The resolution of the radar is 150 m (radial) $\times$ 1.2 degrees (azimuthal). The radar obtains three-dimensional volume scans with 12 elevation angles in 5-min interval. The radar data used in this paper is composited using scans with elevation angles of the bottom scan angles, 1.7 degrees and 3.6 degrees, corresponding to altitudes of 440 m and 940 m at Kanazawa City, respectively. The original data set of XRAIN can be obtained from the DIAS service[1].

2.3 Radio observations of lightning with the FALMA and DALMA

The Fast Antenna Lightning Mapping Array (FALMA) is a lightning mapping system working in the low-frequency band. As described by Wu et al. (2018), the FALMA is capable of three-dimensional (3-D) highly-accurate mapping of lightning channels. However, due to the fact that altitudes of lightning discharges in winter thunderstorms are much lower than in summer ones, the FALMA can only determine 2-D locations in most cases in winter observations (Wu et al., 2020). In order to perform 3-D lightning mapping in winter, we developed a new system called Discone Antenna Lightning Mapping Array (DALMA), working in the median-frequency and high-frequency bands (Wang et al., 2022). During the winter campaign of 2021, we deployed 10 FALMA sites and 12 DALMA sites (Figure 1). Thus, the FALMA provides 2-D location results of lightning discharges and also electric field change waveforms from which we can determine the discharge types. The DALMA provides 3-D location results of lightning discharges.

3 Data Analysis and Results

On 30 December 2021, the typical winter pressure pattern appeared over Japan, and severe thunderstorms passed over Kanazawa from west to east. At 04:07:37 JST (GMT+9 hours), the automatic alert system of gamma-ray glows was triggered by the Cogamo Identification (ID) 53. Figure 2a shows 8-sec-binned count-rate histories in the 3–10 MeV band recorded by Cogamo IDs 62, 23, 33, 53, and 15 for a period encompassing the timing of the glow detection, whose locations are shown in Figure 3. The gamma-ray glow was the first simultaneous detection from a thundercloud with five Cogamo sensors of our citizen science campaign. Two of the five detectors recorded the glow termination coinciding with a lightning flash at 4:08:34.85 JST (Figure 2a) identified by FALMA and DALMA (Figure 2b). In the discharge, Cogamo ID 33 also recorded a short spiky burst (5 counts within 1 ms), which corresponds to a low chance-occurrence probability of 1.66×10^{-10} for the background statistical fluctuations. The independent Compton camera at the same location as Cogamo ID 33 also recorded the spiky burst within 4 ms. We conclude that this burst should be a TGF associated with lightning discharges. We do not discuss any further in this paper but will present more details elsewhere.

[1] https://diasjp.net, which was supported by JAMSTEC

We evaluated the significant count-rate increases over background fluctuations, using the energy band above 3 MeV, which is not affected by the environmental background fluctuations. We fitted the histogram of the 8-sec-binned and 1 hour count-rate histories with the Gaussian function for each detector. As an example, the background fluctuation of the data of Cogamo ID 53 was successfully fitted with an average count rate of 3.38 count sec^{-1} and standard deviation σ of 2.08 count sec^{-1}. Here we set the glow detection threshold at the count rate bins exceeding the 3.5σ significance (e.g., 3.38+2.08×3.5=10.6 count sec^{-1} for ID 53), at which a chance occurrence probability is 0.05% corresponding an expected false detection of 0.11 bins during the 1-hour observation. The glow period exceeding this 3.5σ threshold is shown in red in Figure 2a. The duration ($T_{3.5\sigma}$) of the gamma-ray glow calculated from numbers of bins above 3.5σ were 24, 24, 80, 112, and 56 s, for Cogamo IDs 62, 23, 33, 53, and 15, respectively. In this calculation of the duration, we exclude the TGF events from Cogamo ID 33.

Figure 3a shows the rainfall intensity maps every minute for a period of 04:06–04:09 JST, calculated from the rader reflectivity data. During the period, the high-intensity region was moving toward the east and passing over the Cogamo detectors. We estimated the on-ground horizontal size of the gamma-ray glow (hereafter "glow region") by multiplying the wind speed and the $T_{3.5\sigma}$ duration (see also Wada et al. (2019)). Assuming that the glow region was a circle for the horizontal direction and using the method described in Wada et al. (2019), we estimated the glow region at each detector and plot all of them in Figure 3b. Here we adopted the wind speed and direction at this glow of 21.2 ± 0.8 m s^{-1} and 266.5 degrees (clockwise with respect to the north), respectively, estimated from the XRAIN data. For example, the diameter of the glow region of Cogamo ID 53 is 2.3 km. The size of the glow region perpendicular to the wind direction is estimated from the distance from the north end to the south end of the glow regions of five detectors to be 2.5 km.(Figure 3b).

The FALMA and DALMA identified the lightning flash starting at 04:08:34.8565 JST at the location (36.57816N, 136.66101E) in the vincity of the glow event. The lightning flash first developed northeastward and then southeastward (Figure 3c). In Figure 3d, we compared the locations between the Cogamo-detected glows and the initial signals of the discharges, in which we take into account the move of the glow with the wind. The first distinct five and three discharge signals of FALMA and DALMA, respectively, occurred roughly 420 m and 540 m to the east-northeast of Cogamo ID 62. The lightning flash started inside or in the vicinity of the glow region, within the FALMA horizontal error of a few hundred meters. The low-frequency radio waveform and the altitude of lightning discharge (Figure 2b) indicate that the flash started with a downward negative leader with a large speed of about 3×10^6 m s^{-1}. The downward leader, corresponding to the preliminary breakdown pulses, is followed by a negative return stroke in less than 3 ms. Interestingly, its largest preliminary breakdown pulse (−17 kA) is stronger than the return stroke pulse (−10 kA).

Figure 4a shows the rainfall intensity maps at 04:08 JST for a wide area and Figure 4b shows a vertical cross-section of it along the axis of interest indicated in Figure 4a. The area of high rainfall-intensity was extended from the northwest to southeast for a distance of 11 km, while the glow was observed only in the northwest area across 2 km. In the glow region, high reflectivity exceeding 40 dBZ was found to develop beyond 2 km in height, while in the southeast no glow region with a reflectivity of more than 40 dBZ was found in the lower altitude (<2 km). Figure 4c is the vertical distribution of hydrometeor in the clouds. We applied the hydrometeor classification (HC) method for X-band polarimetric radar data to classify the radar data into eight types of primary precipitation particles: drizzle, rain, wet snow, dry snow, ice crystals, dry graupel, wet graupel, and rain–hail mixture (Kouketsu et al., 2015). We transformed the coordinate system from a polar one to Cartesian grids, using weighted interpolation according to the distance (Cressman, 1959). Wet graupels appeared up to the altitude 2 km above the glow region, whereas they are seen up to the altitudes only 1.5 km above the non-glow area.

4 Discussion and Conclusion

The present citizen science campaign at Kanazawa allowed us to perform high-density and multipoint measurements of a gamma-ray glow (Figure 2). We estimated the horizontal size of the glow to be 2 km in the east-west direction (parallel to the wind direction) and 2.5 km in the north-south direction (perpendicular to the wind direction). The radar–monitored moving clouds of the high reflectivity (>40 dBZ) reached 2 km in altitude (Figure 4b) and wet graupels found in the lower layers (Figure 4c) in the glow region. The characteristics of lightning discharges in Figure 2b suggest a negatively-charged middle layer appearing at 2 km altitude, and the present thundercloud case is likely to have a tripolar charge structure as expected in developed winter thunderclouds formed primarily via upward winds. According to the riming electrification model (Takahashi, 1978), wet graupels are positively charged at the lower layer with a temprature of around -10°C in winter thunderstorms. A downward gamma-ray glow is expected to be radiated from relativistic electrons accelerated in the electric field between this positively-charged lower layer and the negatively-charged middle layer. The radar data (Figure 4b), combined with altitudes of discharges (Figure 2b, see the discussion below), suggests that electrons were accelerated downward in the strong electric field below the negatively-charged middle layer located lower than $\sim$2 km in altitude in our case.

The FALMA and DALMA data allowed us to further compare the initiation of lightning discharges and the gamma-ray glow. The discharges started about 420 m (FALMA) and 540 m (DALMA) away from Cogamo ID 62 (Figure 3d). Taking into account the glow movement with the wind flow (846 m shift from Figure 3b), the initial lightning signals started inside or near the glow region, within the radio measurement error ($\sim$100 m) and estimated horizontal size of the glow ($\sim$510 m). This result suggests the electric-field regions initiating the lightning discharges and relativistic electron acceleration for the gamma-ray glow existed in the same space. As the vertical information, Figure 2b shows that the preliminary breakdown started at an altitude of 1.6 km and propagated downward, ending at 0.5 km in altitude. Assuming that a strong electric field is formed between these two altitudes at 0.5–1.6 km with a strength close to the RREA threshold of 0.28 MV m^{-1} (Babich et al., 2004; Dwyer, 2003), bremsstrahlung from accelerated electrons are detectable on the ground; for example, gamma-ray flux decreases to 28% to the downward direction from the 0.5 km altitude.

The radio signals (Figure 2b) indicated the leader speed 3×10^{6} m s^{-1} at the preliminary breakdown stage, which is about one order of magnitude higher than those in the previously reported lightning flashes (Saba et al., 2009, 2014; Wu et al., 2015; Shi et al., 2019). It is widely believed that a high leader speed is usually associated with a strong ambient electric field (Nag & Rakov, 2009; Shi et al., 2019; Wu et al., 2022). The existence of such a strong vertical electric field is also supported by the strong preliminary breakdown signal (Figure 2b). An interesting possibility is that the flow of relativistic electrons, which works as the source of the gamma-ray glow, may enhance the chance of the initiation of this lightning flash at the $\sim$1.6 km altitude. The ambient electric field around the RREA threshold could increase the free-electron density involved in creating a leader plasma channel to promote the onset of lightning discharges (Francisco et al., 2021). Although the RREA-accelerated electron population alone would not be able to trigger lightning (Coleman & Dwyer, 2006), the augmentation of the free electron population around sharp ice particles could enhance the electric field (Dubinova et al., 2015), which may play a significant role in lightning initiation. This hypothesis is supported by some past balloon experiments; they reported the occurrences of lightning discharges at the vicinity environment of the electric field strength of 0.2 MV m^{-1} (Nicoll,

2012) closer to the RREA threshold and an order of magnitude lower than the classical breakdown threshold in the air of 2.6 MV m^{-1} (Cooray, 2014).

The lightning flash terminated the glow, as detected by two Cogamo detectors (IDs 53 and 62), similar to previously reported events (Tsuchiya et al., 2013; Wada et al., 2019; Wada et al., 2018; Hisadomi et al., 2021). This glow termination means the disappearance of the electric field in the RREA region and the neutralization of the charged layers. Interestingly, Figure 3c suggested that the lightning discharges did not enter the original glow region but propagated along the edge or outside the glow region. The fact implies that the charge cancellation happened quickly after the termination of the glow once the lightning is initiated, and as a result, the lightning channel propagates to the places where the charge separation still remains.

We conjecture that the reason why gamma rays were detected in the northwestern region but not in the southeastern region would be due to some differences in thier meteorological conditions. A working hypothesis is that at the late stage of the life cycle of a thundercloud associated with the weak updrafts, a pocket in the positively-charged lower layer with wet graupels falls to the ground, dragging the charge-separated region toward the ground and providing a detectable condition of the glow. In our case, a potential glow in the southeastern region with falling graupels had likely already ended before the cloud reached our Cogamo detectors; this hypothesis is consistent with the relatively low ($<$1 km) high-reflectivity ($>$40 dBZ) region and observed wet graupel distribution. An alternative scenario is that the electric field condition in the thunderstorm did not develop sufficiently in the southeast region. In the former case, the gamma-ray glow may have occurred before the time 04:08 JST as of Figure 4, but we cannot verify it because there were no detectors in the area. In the coming years, our Thundercloud Project will continue radiation-mapping observations to increase the sample number of gamma-ray glows, extending the first result as reported in this Letter to advance our understanding of thunderstorm physics.

Data Availability Statement

The data used in this paper are available on Zenodo after accepting this paper. [2]

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References

Babich, L., Donskoy, E. N., Il'kaev, R. I., Kutsyk, I. M., & Roussel-Dupre,

[2] Tentatively, the same data set was uploaded to the submission system as supporting information with the file name of data.zip for reviewers to access.

R. A. (2004). Fundamental parameters of a relativistic runaway electron avalanche in air. *Plasma Physics Reports*, *30*, 616–624. (https://doi.org/10.1134/1.1778437)

Chilingarian, A. A., & Sogomonyan, S. B. (2015). Thunderstorm ground enhancements abruptly terminated by the lightning flash. *AGU Fall Meeting Abstracts*, *2015*, AE33A-0463. (https://ui.adsabs.harvard.edu/abs/2015AGUFMAE33A0463C)

Coleman, L. M., & Dwyer, J. R. (2006). Propagation speed of runaway electron avalanches. *Geophysical Research Letters*, *33*(11). (https://doi.org/10.1029/2006GL025863)

Cooray, V. (2014). *The lightning flash, 2nd edition.* IET.

Cressman, G. P. (1959). An operational objective analysis system. *Monthly Weather Review*, *87*(10), 367. (https://doi.org/10.1175/1520-0493(1959)087¡0367:AOOAS¿2.0.CO;2)

Dubinova, A., Rutjes, C., Ebert, U., Buitink, S., Scholten, O., & Trinh, G. T. N. (2015). Prediction of lightning inception by large ice particles and extensive air showers. *Physical Review Letters*, *115*, 015002. (https://doi.org/10.1103/PhysRevLett.115.015002)

Dwyer, J. R. (2003). A fundamental limit on electric fields in air. *Geophysical Research Letters*, *30*(20). (https://doi.org/10.1029/2003GL017781)

Enoto, T., Wada, Y., Furuta, Y., Nakazawa, K., Yuasa, T., Okuda, K., et al. (2017). Photonuclear reactions in lightning discovered from detection of positrons and neutrons. *arXiv e-prints*, arXiv:1711.08044. (https://ui.adsabs.harvard.edu/abs/2017arXiv171108044E)

Francisco, H., Bagheri, B., & Ebert, U. (2021). Electrically isolated propagating streamer heads formed by strong electron attachment. *Plasma Sources Science and Technology*, *30*(2), 025006. (https://dx.doi.org/10.1088/1361-6595/abdaa3)

Goto, Y., & Narita, K. (1992). Observations of winter lightning to an isolate tower. *Journal of Atmospheric Electricity*, *12*(1), 57-60. (https://doi.org/10.1541/jae.12.57)

Gurevich, A. V., Milikh, G. M., & Roussel-Dupre, R. (1992). Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. *Physics Letters A*, *165*(5-6), 463-468. (https://ui.adsabs.harvard.edu/abs/1992PhLA..165..463G)

Hisadomi, S., Nakazawa, K., Wada, Y., Tsuji, Y., Enoto, T., Shinoda, T., et al. (2021). Multiple gamma-ray glows and a downward tgf observed from nearby thunderclouds. *Journal of Geophysical Research: Atmospheres*, *126*(18), e2021JD034543. (https://doi.org/10.1029/2021JD034543)

Kataoka, J., Kishimoto, A., Nishiyama, T., Fujita, T., Takeuchi, K., Kato, T., et al. (2013). Handy compton camera using 3d position-sensitive scintillators coupled with large-area monolithic mppc arrays. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *732*, 403-407. (https://doi.org/10.1016/j.nima.2013.07.018)

Kelley, N. A., Smith, D. M., Dwyer, J. R., Splitt, M., Lazarus, S., Martinez-McKinney, F., et al. (2015). Relativistic electron avalanches as a thunderstorm discharge competing with lightning. *Nature Communications*, *6*, 7845. (https://ui.adsabs.harvard.edu/abs/2015NatCo...6.7845K)

Kouketsu, T., Uyeda, H., Ohigashi, T., Oue, M., Takeuchi, H., Shinoda, T., et al. (2015). A hydrometeor classification method for x-band polarimetric radar: Construction and validation focusing on solid hydrometeors under moist environments. *Atmospheric and Oceanic Technology*, *32*, 2052-2074. (https://doi.org/10.1175/JTECH-D-14-00124.1)

Kuriyama, E., Masubuchi, M., Koshikawa, N., Iwashita, R., Omata, A., Kanda, T., et al. (2022). Compton camera imaging of a gamma-ray glow from a thunderstorm. *Geophysical Research Letters*, *49*(19), e2022GL100139. (https://doi.org/10.1029/2022GL100139)

Köhn, C., Diniz, G., & Harakeh, M. N. (2017). Production mechanisms of leptons, photons, and hadrons and their possible feedback close to lightning leaders. *Journal of Geophysical Research: Atmospheres*, *122*(2), 1365-1383. (https://doi.org/10.1002/2016JD025445)

Nag, A., & Rakov, V. A. (2009). Some inferences on the role of lower positive charge region in facilitating different types of lightning. *Geophysical Research Letters*, *36*(5). (https://doi.org/10.1029/2008GL036783)

Nicoll, K. (2012). Measurements of atmospheric electricity aloft. *Surv Geophys*, *33*, 991–1057. (https://doi.org/10.1007/s10712-012-9188-9)

Omata, A., Kataoka, J., Fujieda, K., Sato, S., Kuriyama, E., Kato, H., et al. (2020). Performance demonstration of a hybrid compton camera with an active pinhole for wide-band x-ray and gamma-ray imaging. *scientific reports*, *10*(14064). (https://doi.org/10.1038/s41598-020-71019-5)

Saba, M. M. F., Campos, L. Z. S., Krider, E. P., & Pinto Jr., O. (2009). High-speed video observations of positive ground flashes produced by intracloud lightning. *Geophysical Research Letters*, *36*(12). (https://doi.org/10.1029/2009GL038791)

Saba, M. M. F., Campos, L. Z. S., Krider, E. P., & Pinto Jr., O. (2014). High-speed video observations of natural cloud-to-ground lightning leaders – a statistical analysis. *Atmospheric Research*, *135-136*, 285-305.

Shi, D., Wang, D., Wu, T., & Takagi, N. (2019). Correlation between the first return stroke of negative cg lightning and its preceding discharge processes. *Geophysical Research: Atmospheres*, *124*(15), 8501-8510. (https://doi.org/10.1029/2019JD030593)

Smith, D. M., Lopez, L. I., Lin, R. P., & Barrington-Leigh, C. P. (2005). Terrestrial gamma-ray flashes observed up to 20 mev. *Science*, *307*(5712), 1085-1088. (https://ui.adsabs.harvard.edu/abs/2005Sci...307.1085S)

Takahashi, T. (1978). Riming electrification as a charge generation mechanism in thunderstorms. *Atmospheric Sciences*, *35*, 1536–1548. (https://doi.org/10.1175/1520-0469(1978)035¡1536:REAACG¿2.0.CO;2)

Tsuchiya, H., Enoto, T., Iwata, K., Yamada, S., Yuasa, T., Kitaguchi, T., et al. (2013). Hardening and termination of long-duration γ rays detected prior to lightning. *Physical Review Letters*, *111*(1), 015001. (https://ui.adsabs.harvard.edu/abs/2013PhRvL.111a5001T)

Tsuchiya, H., Enoto, T., Yamada, S., Yuasa, T., Kawaharada, M., Kitaguchi, T., et al. (2007). Detection of high-energy gamma rays from winter thunderclouds. *Physics Review Letters*, *99*(4), 165002. (https://link.aps.org/doi/10.1103/PhysRevLett.99.165002)

Wada, Y., Bowers, G. S., Enoto, T., Kamogawa, M., Nakamura, Y., Morimoto, T., et al. (2018). Termination of electron acceleration in thundercloud by intracloud/intercloud discharge. *Geophysical Research Letters*, *45*(11), 5700-5707. (https://doi.org/10.1029/2018GL077784)

Wada, Y., Enoto, T., Nakamura, Y., Furuta, Y., Yuasa, T., Nakazawa, K., et al. (2019). Gamma-ray glow preceding downward terrestrial gamma-ray flash. *Communications Physics*, *2*(1), 67. (https://ui.adsabs.harvard.edu/abs/2019CmPhy...2...67W)

Wada, Y., Matsumoto, T., Enoto, T., Nakazawa, K., Yuasa, T., Furuta, Y., et al. (2021). Catalog of gamma-ray glows during four winter seasons in japan. *Physical Review Research*, *3*(4), 043117. (https://doi.org/10.48550/arXiv.2108.01829)

Wang, D., Wu, T., Huang, H., Yang, J., & Yamamoto, K. (2022). 3d mapping of winter lightning in japan with an array of discone antennas. *IEEJ Transactions on Electrical and Electronic Engineering*, *17*(11), 1606-1612.

(https://doi.org/10.1002/tee.23667)
Wu, T., Wang, D., & Takagi, N. (2018). Lightning mapping with an array of fast antennas. *Geophysical Research Letters*, *45*(8), 3698-3705. (https://doi.org/10.1002/2018GL077628)
Wu, T., Wang, D., & Takagi, N. (2020). Multiple-stroke positive cloud-to-ground lightning observed by the falma in winter thunderstorms in japan. *Geophysical Research: Atmospheres*, *125*(20), e2020JD033039. (https://doi.org/10.1029/2020JD033039)
Wu, T., Wang, D., & Takagi, N. (2022). On the intensity of first return strokes in positive cloud-to-ground lightning in winter. *Geophysical Research: Atmospheres*, *127*(22), e2022JD037282. (https://doi.org/10.1029/2022JD037282)
Wu, T., Yoshida, S., Akiyama, Y., Stock, M., Ushio, T., & Kawasaki, Z. (2015). Preliminary breakdown of intracloud lightning: Initiation altitude, propagation speed, pulse train characteristics, and step length estimation. *Geophysical Research: Atmospheres*, *120*(18), 9071-9086. (https://doi.org/10.1002/2015JD023546)
Yuasa, T., Wada, Y., Enoto, T., Furuta, Y., Tsuchiya, H., Hisadomi, S., et al. (2020). Thundercloud project: Exploring high-energy phenomena in thundercloud and lightning. *Progress of Theoretical and Experimental Physics*, *2020*(10), 103H01. (https://doi.org/10.1093/ptep/ptaa115)

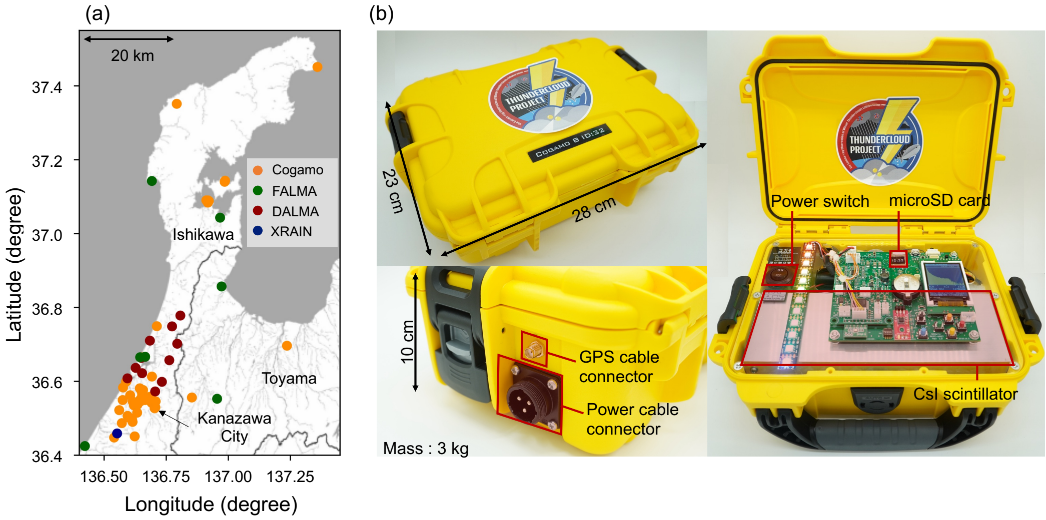

Figure 1. (a) Map of our observation sites in the Noto Peninsula. The orange, green, red, and blue circles show the locations of Cogamo detectors, the FALMA sites, DALMA sites, and the XRAIN Nomi Radar site, respectively. (b) Photographs of our portable Cogamo radiation detector.

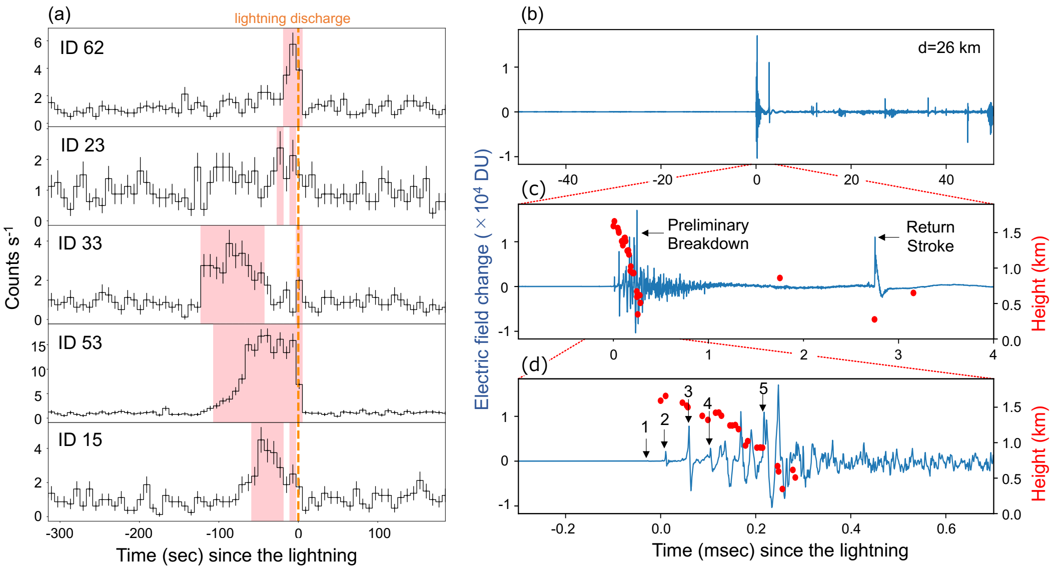

Figure 2. (a) 8-sec-binned count rate histories of radiation in the 3–10 MeV band recorded by five Cogamo detectors of, from the top to bottom panels, Cogamo IDs 62 (36.57N, 136.65E), 23 (36.57N, 136.65E), 33(36.56N, 136.65E), 53 (36.56N, 136.65E), and 15 (36.55N, 136.65E), in the order of the north to south. Error bars are statistical 1σ. The time origin is 04:08:34.8565 JST on 30 December, 2021, which corresponds to the first signal of the lightning discharge recorded by FALMA and DALMA. Data bins with detection significance exceeding 3.5σ are marked in red. (b–d) Preliminary breakdown pulses recorded by FALMA (blue lines, the left vertical axis) and their heights mapped by DALMA (red markers, the right axis). The time origin is the same as panel (a). The five pulses with numbers indicated are used for the location analysis.

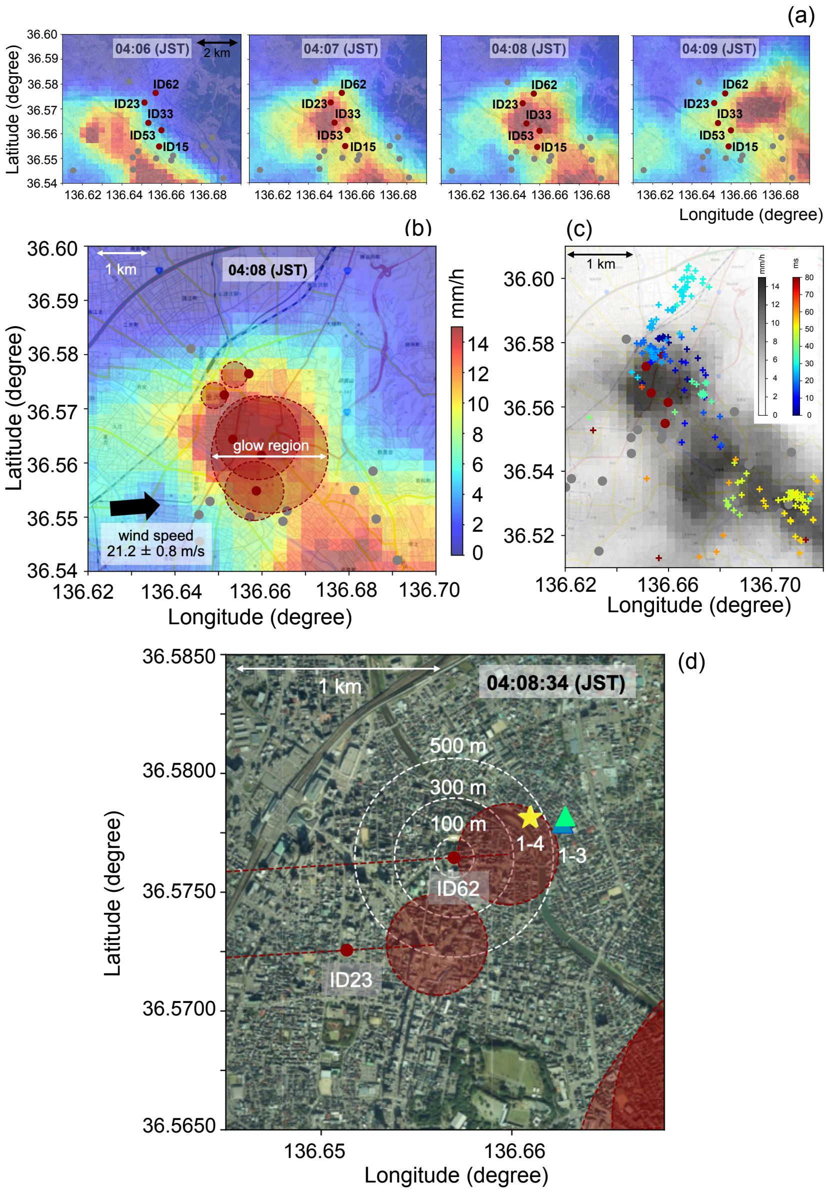

Figure 3. (a) XRAIN radar rainfall intensity maps in Kanazawa at every minute between 04:06–04:09 JST on 30 December, 2021. Locations of the Cogamo detectors are indicated in circle symbols, with their ID numbers. Red and gray circles show detectors with and without the gamma-ray glow detections, respectively, for the event reported in this paper. The overlaid topographic map is taken from the Geospatial Information Authority of Japan. (b) Same as panel (a) at 04:08 JST, but our estimated regions of gamma-ray radiation at individual Cogamo detectors are overlaid. The wind speed (21.2±0.8 m s^{-1}) and the direction of the westerly wind 266.5 degrees (clockwise with respect to the north) are also indicated. (c) Locations of lightning discharges (cross marks) detected by FALMA compared with the Cogamo locations (circle marks) and rainfall intensity (background in grayscale). The colors of the cross marks represent elapsed time of discharges from the time origin of 04:08:34.8565 JST (right-side color bar). (d) Zoom-up figure at 04:08:34 JST around the initial stage of the lightning flash. The lighting signals detected by FALMA and DALMA are indicated in star markers and triangles, respectively, with the numbers (1–4 and 1–3) corresponding to the orders of discharges (the first to the third signals and to the fourth signals). These signals indicate the starting position of the lightning discharges. The red marker is the Cogamo ID 62 location, and red-filled circles indicate the estimated gamma-ray glow regions at the timing of the lightning discharge.

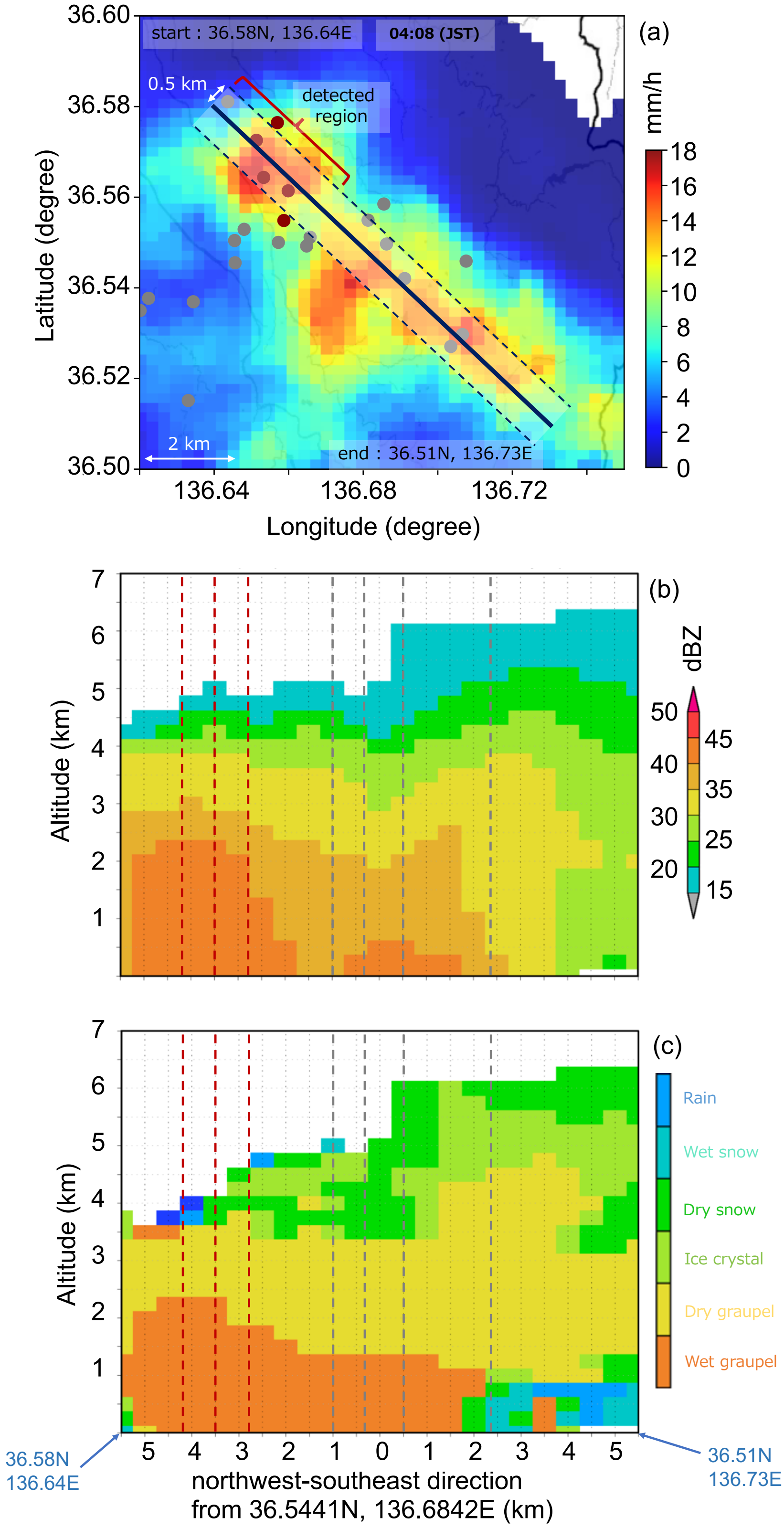

Figure 4. (a) Rainfall intensity map at 04:08 JST, the same as Figure 3 but showing a wider region. The blue solid line and dotted lines indicate the vertical cross-section to be used in panels b and c, and the distance of 500 m away from the cross-section, respectively. (b) Vertical cross-sectional view of the corrected reflectivity factor. Red vertical dotted lines and gray dotted lines indicate the locations of Cogamo detectors with and without gamma-ray detections, respectively, for the event within the 500 m region around the cross-sectional line. The central location is at (36.5441N, 136.6842E). (c) Same as Panel (b), but for the particle identification.

Citizen science observation of a gamma-ray glow associated with the initiation of a lightning flash

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Key Points:

- We started the citizen science “Thundercloud Project”, a multi-point observation campaign of gamma-ray glows from thunderstorms.
- On 30 December 2021, five radiation monitors detected a 2-km-long size gamma-ray glow, which suddenly terminated with a lightning flash.
- Two radio mapping systems of lightning identified the initiation of the discharges, which started at a location above the glow region.

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Abstract

Gamma-ray glows are observational evidence of relativistic electron acceleration due to the electric field in thunderclouds. However, it is yet to be understood whether such relativistic electrons contribute to the initiation of lightning discharges. To tackle this question, we started the citizen science "Thundercloud Project", where we map radiation measurements of glows from winter thunderclouds along Japan sea coast area. We developed and deployed 58 compact gamma-ray monitors at the end of 2021. On 30 December 2021, five monitors simultaneously detected a glow with its radiation distribution horizontally extending for 2 km. The glow terminated coinciding with a lightning flash at 04:08:34 JST, which was recorded by the two radio-band lightning mapping systems, FALMA and DALMA. The initial discharges during the preliminary breakdown started above the glow, i.e., in vicinity of the electron acceleration site. This result provides one example of possible connections between electron acceleration and lightning initiation.

Plain Language Summary

Thunderstorms are natural particle accelerators. The strong electric field inside thunderclouds accelerates relativistic electrons, which emit gamma rays via interaction with the atmosphere. High-energy photons generated in this process have been observed as radiation enhancements called gamma-ray glows. Winter thunderclouds along the sea of Japan are an ideal target for monitoring glows because their altitudes are usually sufficiently low for the generated gamma-ray photons to reach the ground. We started a new citizen science "Thundercloud Project" in this area, where we distributed radiation detectors to citizen supporters to observe glows and to reveal their relationship with the aerological condition and lightning discharges. On 30 December 2021, five of those sensors detected a glow from a single thundercloud. Two of them recorded a sudden termination of the glow coinciding with a lightning flash, which was monitored by our two radio mapping systems of FALMA and DALMA. The initial discharges of the flash started at a location about 1.6 km above the glow region with an unusually fast downward progression. This paper is the first report of our citizen science project. We discuss the possibility that accelerated electrons contribute to the initiation of lightning discharges.

1 Introduction

Strong electric fields inside thunderclouds accelerate electrons up to relativistic energy and cause several types of high-energy atmospheric phenomena. One example is terrestrial gamma-ray flashes (TGFs) coinciding with lightning discharges (Smith et al., 2005; Wada et al., 2019; Enoto et al., 2017). Other phenomena "gamma-ray glows", also referred to as Thunderstorm Ground Enhancements (TGE), are radiation enhancements in the MeV range for a duration of tens of seconds to minutes during thunderstorm passages detected in ground experiments (Tsuchiya et al., 2007; Chilingarian & Sogomonyan, 2015; Wada et al., 2021).

Gamma-ray glows are thought to be bremsstrahlung from relativistic electrons accelerated through the Relativistic Runaway Electron Acceleration (RREA) process by the strong electric field (≥ 0.28 MV m^{-1}) in the thunderclouds (Dwyer, 2003; Babich et al., 2004; Gurevich et al., 1992; Kelley et al., 2015). However, many unanswered questions still remain about the characteristics, meteorological conditions, mechanism of gamma-ray glows, and their relationship with lightning discharges. In particular, it is an interesting question whether the accelerated relativistic electrons in a glow can eventually enhance the chance of lightning initiation. Observations of glow can provide a valuable indicator of the RREA electron acceleration in clouds potentially related to the initiation of lightning.

Gamma rays are attenuated in the atmosphere; the mean free path for, for example, a 10 MeV photon is about 400 m at the ground pressure (Köhn et al., 2017). Hence, ground-based measurements can detect glows from low-altitude clouds with base altitudes of not much greater than the gamma-ray mean free path. During winter in Japan, cold and dry air from the Siberia air mass frequently flows over the Tsushima warm current in the Japan Sea and brings low-altitude thunderclouds with cloud bases of 0.2–0.8 km (Goto & Narita, 1992) in the north coastal area of Japan. The area is ideal for ground observations of gamma-ray glow. We have installed an increasing number of multi-point radiation detectors in and around Kanazawa (Tsuchiya et al., 2007; Tsuchiya et al., 2013; Wada et al., 2018; Yuasa et al., 2020), which have recorded about 2 glow events per detector site per year (Wada et al., 2021).

Given that the atmospheric gamma-ray mean free path is ∼400 m, it is desirable to place detectors at intervals of a few hundred meters to track in detail the time variation of gamma rays emitted from a moving thundercloud. The observation system with this high-density grid would allow us to potentially answer several unsolved questions of high-energy atmospheric physics, including (1) the conditions for a glow to start and end, (2) the type of cloud where glows occur, e.g., size and structure of the electron-acceleration region, and (3) relationship between glows and lightning discharges. Then, we launched the new citizen science "Thundercloud Project" at Kanazawa in 2018, and present our first result of this project.

2 Methods and Observations

2.1 Citizen science "Thundercloud Project"

For the citizen science "Thundercloud Project", we newly developed a portable, easy-to-operate radiation detector named "COmpact GAmma-ray MOnitor (Cogamo)". Every winter, our project researchers send the Cogamo detectors to citizen supporters after conducting detector maintenance. Citizen supporters receive and deploy them in their houses along Japan sea coast area and join the team of radiation observations. In the Japanese fiscal year (FY) 2021, we constructed a large-scale and multi-point observation network with 58 Cogamos installed in the Ishikawa, Toyama, and Niigata prefectures. Among them, the region in and around Kanazawa city had the highest detector density with 16 radiation detectors installed in a 5 km square area. Figure 1a shows almost all Cogamo locations during the FY2021 winter campaign from December 2021 to March 2022.

The Cogamo detector is a small (23 cm × 28 cm × 10 cm) and lightweight (3 kg) radiation monitor, using a CsI (Tl) scintillator (5 cm × 5 cm × 15 cm) coupled with a Silicon Photomultipliers (SiPMs) MPPC (Multi-Pixel Photon Counter) as a photo sensor (Figure 1b). The energy range for gamma-ray spectroscopy is the ∼0.2–10 MeV band. The detector acquires the energy deposit and arrival time of each radiation event and records them into a microSD card. The time tagging is performed using GPS signals. In addition, 20-sec bin count rates in 6 energy bands for 0.2–0.5, 0.5–1, 1–2, 2–3, 3–8, and >8 MeV, GPS status, ambient temperature, humidity, and optical luminosity are recorded on the microSD card and are also sent to the web server for a quick-look purpose. An observation is started simply by connecting a GPS cable and a power cable and then turning on the power switch. Energy calibration of the Cogamo detector was performed for each file of one-hour data when analyzing, using environmental background radiation lines of ^{40}K (1.46 MeV) and ^{208}Tl (2.61 MeV).

In FY2021, we also prepared an automatic gamma-ray glow real-time alert system on our web server to remotely monitor observations. With this system, we calculate the moving average of the count rate of the specified energy bands among the 6 bands (e.g., >1 MeV). Assuming the Gaussian distribution with statistical fluctuations from the latest 20-second count rate values, we send an alert by means of posting it on Twitter when the latest count rate exceeds the predefined threshold. The project summary will be reported in subsequent papers. In FY2021 only, we also conducted optical camera and gamma-ray Compton camera imaging (Kataoka et al., 2013; Omata et al., 2020; Kuriyama et al., 2022) from a high-rise window of a hotel in Kanazawa.

2.2 XRAIN meteorological radar

To determine the movements of thunderclouds above the Cogamo detectors, we use the eXtended RAdar Information Network (XRAIN) operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan. We used the data obtained with the XRAIN Nomi radar (Figure 1a), which is located 15 km away from Kanazawa in the southeast direction. The observation area is within 80 km of the radar, which covers around Kanazawa. The resolution of the radar is 150 m (radial) $\times$ 1.2 degrees (azimuthal). The radar obtains three-dimensional volume scans with 12 elevation angles in 5-min interval. The radar data used in this paper is composited using scans with elevation angles of the bottom scan angles, 1.7 degrees and 3.6 degrees, corresponding to altitudes of 440 m and 940 m at Kanazawa City, respectively. The original data set of XRAIN can be obtained from the DIAS service[1].

2.3 Radio observations of lightning with the FALMA and DALMA

The Fast Antenna Lightning Mapping Array (FALMA) is a lightning mapping system working in the low-frequency band. As described by Wu et al. (2018), the FALMA is capable of three-dimensional (3-D) highly-accurate mapping of lightning channels. However, due to the fact that altitudes of lightning discharges in winter thunderstorms are much lower than in summer ones, the FALMA can only determine 2-D locations in most cases in winter observations (Wu et al., 2020). In order to perform 3-D lightning mapping in winter, we developed a new system called Discone Antenna Lightning Mapping Array (DALMA), working in the median-frequency and high-frequency bands (Wang et al., 2022). During the winter campaign of 2021, we deployed 10 FALMA sites and 12 DALMA sites (Figure 1). Thus, the FALMA provides 2-D location results of lightning discharges and also electric field change waveforms from which we can determine the discharge types. The DALMA provides 3-D location results of lightning discharges.

3 Data Analysis and Results

On 30 December 2021, the typical winter pressure pattern appeared over Japan, and severe thunderstorms passed over Kanazawa from west to east. At 04:07:37 JST (GMT+9 hours), the automatic alert system of gamma-ray glows was triggered by the Cogamo Identification (ID) 53. Figure 2a shows 8-sec-binned count-rate histories in the 3–10 MeV band recorded by Cogamo IDs 62, 23, 33, 53, and 15 for a period encompassing the timing of the glow detection, whose locations are shown in Figure 3. The gamma-ray glow was the first simultaneous detection from a thundercloud with five Cogamo sensors of our citizen science campaign. Two of the five detectors recorded the glow termination coinciding with a lightning flash at 4:08:34.85 JST (Figure 2a) identified by FALMA and DALMA (Figure 2b). In the discharge, Cogamo ID 33 also recorded a short spiky burst (5 counts within 1 ms), which corresponds to a low chance-occurrence probability of 1.66×10^{-10} for the background statistical fluctuations. The independent Compton camera at the same location as Cogamo ID 33 also recorded the spiky burst within 4 ms. We conclude that this burst should be a TGF associated with lightning discharges. We do not discuss any further in this paper but will present more details elsewhere.

[1] https://diasjp.net, which was supported by JAMSTEC

We evaluated the significant count-rate increases over background fluctuations, using the energy band above 3 MeV, which is not affected by the environmental background fluctuations. We fitted the histogram of the 8-sec-binned and 1 hour count-rate histories with the Gaussian function for each detector. As an example, the background fluctuation of the data of Cogamo ID 53 was successfully fitted with an average count rate of 3.38 count sec^{-1} and standard deviation σ of 2.08 count sec^{-1}. Here we set the glow detection threshold at the count rate bins exceeding the 3.5σ significance (e.g., $3.38+2.08\times3.5=10.6$ count sec^{-1} for ID 53), at which a chance occurrence probability is 0.05% corresponding an expected false detection of 0.11 bins during the 1-hour observation. The glow period exceeding this 3.5σ threshold is shown in red in Figure 2a. The duration ($T_{3.5\sigma}$) of the gamma-ray glow calculated from numbers of bins above 3.5σ were 24, 24, 80, 112, and 56 s, for Cogamo IDs 62, 23, 33, 53, and 15, respectively. In this calculation of the duration, we exclude the TGF events from Cogamo ID 33.

Figure 3a shows the rainfall intensity maps every minute for a period of 04:06–04:09 JST, calculated from the rader reflectivity data. During the period, the high-intensity region was moving toward the east and passing over the Cogamo detectors. We estimated the on-ground horizontal size of the gamma-ray glow (hereafter "glow region") by multiplying the wind speed and the $T_{3.5\sigma}$ duration (see also Wada et al. (2019)). Assuming that the glow region was a circle for the horizontal direction and using the method described in Wada et al. (2019), we estimated the glow region at each detector and plot all of them in Figure 3b. Here we adopted the wind speed and direction at this glow of 21.2 ± 0.8 m s^{-1} and 266.5 degrees (clockwise with respect to the north), respectively, estimated from the XRAIN data. For example, the diameter of the glow region of Cogamo ID 53 is 2.3 km. The size of the glow region perpendicular to the wind direction is estimated from the distance from the north end to the south end of the glow regions of five detectors to be 2.5 km.(Figure 3b).

The FALMA and DALMA identified the lightning flash starting at 04:08:34.8565 JST at the location (36.57816N, 136.66101E) in the vincity of the glow event. The lightning flash first developed northeastward and then southeastward (Figure 3c). In Figure 3d, we compared the locations between the Cogamo-detected glows and the initial signals of the discharges, in which we take into account the move of the glow with the wind. The first distinct five and three discharge signals of FALMA and DALMA, respectively, occurred roughly 420 m and 540 m to the east-northeast of Cogamo ID 62. The lightning flash started inside or in the vicinity of the glow region, within the FALMA horizontal error of a few hundred meters. The low-frequency radio waveform and the altitude of lightning discharge (Figure 2b) indicate that the flash started with a downward negative leader with a large speed of about 3×10^{6} m s^{-1}. The downward leader, corresponding to the preliminary breakdown pulses, is followed by a negative return stroke in less than 3 ms. Interestingly, its largest preliminary breakdown pulse (-17 kA) is stronger than the return stroke pulse (-10 kA).

Figure 4a shows the rainfall intensity maps at 04:08 JST for a wide area and Figure 4b shows a vertical cross-section of it along the axis of interest indicated in Figure 4a. The area of high rainfall-intensity was extended from the northwest to southeast for a distance of 11 km, while the glow was observed only in the northwest area across 2 km. In the glow region, high reflectivity exceeding 40 dBZ was found to develop beyond 2 km in height, while in the southeast no glow region with a reflectivity of more than 40 dBZ was found in the lower altitude (<2 km). Figure 4c is the vertical distribution of hydrometeor in the clouds. We applied the hydrometeor classification (HC) method for X-band polarimetric radar data to classify the radar data into eight types of primary precipitation particles: drizzle, rain, wet snow, dry snow, ice crystals, dry graupel, wet graupel, and rain–hail mixture (Kouketsu et al., 2015). We transformed the coordinate system from a polar one to Cartesian grids, using weighted interpolation according to the distance (Cressman, 1959). Wet graupels appeared up to the altitude 2 km above the glow region, whereas they are seen up to the altitudes only 1.5 km above the non-glow area.

4 Discussion and Conclusion

The present citizen science campaign at Kanazawa allowed us to perform high-density and multipoint measurements of a gamma-ray glow (Figure 2). We estimated the horizontal size of the glow to be 2 km in the east-west direction (parallel to the wind direction) and 2.5 km in the north-south direction (perpendicular to the wind direction). The radar–monitored moving clouds of the high reflectivity (>40 dBZ) reached 2 km in altitude (Figure 4b) and wet graupels found in the lower layers (Figure 4c) in the glow region. The characteristics of lightning discharges in Figure 2b suggest a negatively-charged middle layer appearing at 2 km altitude, and the present thundercloud case is likely to have a tripolar charge structure as expected in developed winter thunderclouds formed primarily via upward winds. According to the riming electrification model (Takahashi, 1978), wet graupels are positively charged at the lower layer with a temprature of around -10°C in winter thunderstorms. A downward gamma-ray glow is expected to be radiated from relativistic electrons accelerated in the electric field between this positively-charged lower layer and the negatively-charged middle layer. The radar data (Figure 4b), combined with altitudes of discharges (Figure 2b, see the discussion below), suggests that electrons were accelerated downward in the strong electric field below the negatively-charged middle layer located lower than $\sim$2 km in altitude in our case.

The FALMA and DALMA data allowed us to further compare the initiation of lightning discharges and the gamma-ray glow. The discharges started about 420 m (FALMA) and 540 m (DALMA) away from Cogamo ID 62 (Figure 3d). Taking into account the glow movement with the wind flow (846 m shift from Figure 3b), the initial lightning signals started inside or near the glow region, within the radio measurement error ($\sim$100 m) and estimated horizontal size of the glow ($\sim$510 m). This result suggests the electric-field regions initiating the lightning discharges and relativistic electron acceleration for the gamma-ray glow existed in the same space. As the vertical information, Figure 2b shows that the preliminary breakdown started at an altitude of 1.6 km and propagated downward, ending at 0.5 km in altitude. Assuming that a strong electric field is formed between these two altitudes at 0.5–1.6 km with a strength close to the RREA threshold of 0.28 MV m^{-1} (Babich et al., 2004; Dwyer, 2003), bremsstrahlung from accelerated electrons are detectable on the ground; for example, gamma-ray flux decreases to 28% to the downward direction from the 0.5 km altitude.

The radio signals (Figure 2b) indicated the leader speed 3×10^{6} m s^{-1} at the preliminary breakdown stage, which is about one order of magnitude higher than those in the previously reported lightning flashes (Saba et al., 2009, 2014; Wu et al., 2015; Shi et al., 2019). It is widely believed that a high leader speed is usually associated with a strong ambient electric field (Nag & Rakov, 2009; Shi et al., 2019; Wu et al., 2022). The existence of such a strong vertical electric field is also supported by the strong preliminary breakdown signal (Figure 2b). An interesting possibility is that the flow of relativistic electrons, which works as the source of the gamma-ray glow, may enhance the chance of the initiation of this lightning flash at the $\sim$1.6 km altitude. The ambient electric field around the RREA threshold could increase the free-electron density involved in creating a leader plasma channel to promote the onset of lightning discharges (Francisco et al., 2021). Although the RREA-accelerated electron population alone would not be able to trigger lightning (Coleman & Dwyer, 2006), the augmentation of the free electron population around sharp ice particles could enhance the electric field (Dubinova et al., 2015), which may play a significant role in lightning initiation. This hypothesis is supported by some past balloon experiments; they reported the occurrences of lightning discharges at the vicinity environment of the electric field strength of 0.2 MV m^{-1} (Nicoll,

2012) closer to the RREA threshold and an order of magnitude lower than the classical breakdown threshold in the air of 2.6 MV m^{-1} (Cooray, 2014).

The lightning flash terminated the glow, as detected by two Cogamo detectors (IDs 53 and 62), similar to previously reported events (Tsuchiya et al., 2013; Wada et al., 2019; Wada et al., 2018; Hisadomi et al., 2021). This glow termination means the disappearance of the electric field in the RREA region and the neutralization of the charged layers. Interestingly, Figure 3c suggested that the lightning discharges did not enter the original glow region but propagated along the edge or outside the glow region. The fact implies that the charge cancellation happened quickly after the termination of the glow once the lightning is initiated, and as a result, the lightning channel propagates to the places where the charge separation still remains.

We conjecture that the reason why gamma rays were detected in the northwestern region but not in the southeastern region would be due to some differences in thier meteorological conditions. A working hypothesis is that at the late stage of the life cycle of a thundercloud associated with the weak updrafts, a pocket in the positively-charged lower layer with wet graupels falls to the ground, dragging the charge-separated region toward the ground and providing a detectable condition of the glow. In our case, a potential glow in the southeastern region with falling graupels had likely already ended before the cloud reached our Cogamo detectors; this hypothesis is consistent with the relatively low (<1 km) high-reflectivity (>40 dBZ) region and observed wet graupel distribution. An alternative scenario is that the electric field condition in the thunderstorm did not develop sufficiently in the southeast region. In the former case, the gamma-ray glow may have occurred before the time 04:08 JST as of Figure 4, but we cannot verify it because there were no detectors in the area. In the coming years, our Thundercloud Project will continue radiation-mapping observations to increase the sample number of gamma-ray glows, extending the first result as reported in this Letter to advance our understanding of thunderstorm physics.

Data Availability Statement

The data used in this paper are available on Zenodo after accepting this paper. [2]

Acknowledgments

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References

Babich, L., Donskoy, E. N., Il'kaev, R. I., Kutsyk, I. M., & Roussel-Dupre,

[2] Tentatively, the same data set was uploaded to the submission system as supporting information with the file name of data.zip for reviewers to access.

R. A. (2004). Fundamental parameters of a relativistic runaway electron avalanche in air. *Plasma Physics Reports*, *30*, 616–624. (https://doi.org/10.1134/1.1778437)

Chilingarian, A. A., & Sogomonyan, S. B. (2015). Thunderstorm ground enhancements abruptly terminated by the lightning flash. *AGU Fall Meeting Abstracts*, *2015*, AE33A-0463. (https://ui.adsabs.harvard.edu/abs/2015AGUFMAE33A0463C)

Coleman, L. M., & Dwyer, J. R. (2006). Propagation speed of runaway electron avalanches. *Geophysical Research Letters*, *33*(11). (https://doi.org/10.1029/2006GL025863)

Cooray, V. (2014). *The lightning flash, 2nd edition.* IET.

Cressman, G. P. (1959). An operational objective analysis system. *Monthly Weather Review*, *87*(10), 367. (https://doi.org/10.1175/1520-0493(1959)087¡0367:AOOAS¿2.0.CO;2)

Dubinova, A., Rutjes, C., Ebert, U., Buitink, S., Scholten, O., & Trinh, G. T. N. (2015). Prediction of lightning inception by large ice particles and extensive air showers. *Physical Review Letters*, *115*, 015002. (https://doi.org/10.1103/PhysRevLett.115.015002)

Dwyer, J. R. (2003). A fundamental limit on electric fields in air. *Geophysical Research Letters*, *30*(20). (https://doi.org/10.1029/2003GL017781)

Enoto, T., Wada, Y., Furuta, Y., Nakazawa, K., Yuasa, T., Okuda, K., et al. (2017). Photonuclear reactions in lightning discovered from detection of positrons and neutrons. *arXiv e-prints*, arXiv:1711.08044. (https://ui.adsabs.harvard.edu/abs/2017arXiv171108044E)

Francisco, H., Bagheri, B., & Ebert, U. (2021). Electrically isolated propagating streamer heads formed by strong electron attachment. *Plasma Sources Science and Technology*, *30*(2), 025006. (https://dx.doi.org/10.1088/1361-6595/abdaa3)

Goto, Y., & Narita, K. (1992). Observations of winter lightning to an isolate tower. *Journal of Atmospheric Electricity*, *12*(1), 57-60. (https://doi.org/10.1541/jae.12.57)

Gurevich, A. V., Milikh, G. M., & Roussel-Dupre, R. (1992). Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. *Physics Letters A*, *165*(5-6), 463-468. (https://ui.adsabs.harvard.edu/abs/1992PhLA..165..463G)

Hisadomi, S., Nakazawa, K., Wada, Y., Tsuji, Y., Enoto, T., Shinoda, T., et al. (2021). Multiple gamma-ray glows and a downward tgf observed from nearby thunderclouds. *Journal of Geophysical Research: Atmospheres*, *126*(18), e2021JD034543. (https://doi.org/10.1029/2021JD034543)

Kataoka, J., Kishimoto, A., Nishiyama, T., Fujita, T., Takeuchi, K., Kato, T., et al. (2013). Handy compton camera using 3d position-sensitive scintillators coupled with large-area monolithic mppc arrays. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *732*, 403-407. (https://doi.org/10.1016/j.nima.2013.07.018)

Kelley, N. A., Smith, D. M., Dwyer, J. R., Splitt, M., Lazarus, S., Martinez-McKinney, F., et al. (2015). Relativistic electron avalanches as a thunderstorm discharge competing with lightning. *Nature Communications*, *6*, 7845. (https://ui.adsabs.harvard.edu/abs/2015NatCo...6.7845K)

Kouketsu, T., Uyeda, H., Ohigashi, T., Oue, M., Takeuchi, H., Shinoda, T., et al. (2015). A hydrometeor classification method for x-band polarimetric radar: Construction and validation focusing on solid hydrometeors under moist environments. *Atmospheric and Oceanic Technology*, *32*, 2052-2074. (https://doi.org/10.1175/JTECH-D-14-00124.1)

Kuriyama, E., Masubuchi, M., Koshikawa, N., Iwashita, R., Omata, A., Kanda, T., et al. (2022). Compton camera imaging of a gamma-ray glow from a thunderstorm. *Geophysical Research Letters*, *49*(19), e2022GL100139. (https://doi.org/10.1029/2022GL100139)

Köhn, C., Diniz, G., & Harakeh, M. N. (2017). Production mechanisms of leptons, photons, and hadrons and their possible feedback close to lightning leaders. *Journal of Geophysical Research: Atmospheres*, *122*(2), 1365-1383. (https://doi.org/10.1002/2016JD025445)

Nag, A., & Rakov, V. A. (2009). Some inferences on the role of lower positive charge region in facilitating different types of lightning. *Geophysical Research Letters*, *36*(5). (https://doi.org/10.1029/2008GL036783)

Nicoll, K. (2012). Measurements of atmospheric electricity aloft. *Surv Geophys*, *33*, 991–1057. (https://doi.org/10.1007/s10712-012-9188-9)

Omata, A., Kataoka, J., Fujieda, K., Sato, S., Kuriyama, E., Kato, H., et al. (2020). Performance demonstration of a hybrid compton camera with an active pinhole for wide-band x-ray and gamma-ray imaging. *scientific reports*, *10*(14064). (https://doi.org/10.1038/s41598-020-71019-5)

Saba, M. M. F., Campos, L. Z. S., Krider, E. P., & Pinto Jr., O. (2009). High-speed video observations of positive ground flashes produced by intracloud lightning. *Geophysical Research Letters*, *36*(12). (https://doi.org/10.1029/2009GL038791)

Saba, M. M. F., Campos, L. Z. S., Krider, E. P., & Pinto Jr., O. (2014). High-speed video observations of natural cloud-to-ground lightning leaders – a statistical analysis. *Atmospheric Research*, *135-136*, 285-305.

Shi, D., Wang, D., Wu, T., & Takagi, N. (2019). Correlation between the first return stroke of negative cg lightning and its preceding discharge processes. *Geophysical Research: Atmospheres*, *124*(15), 8501-8510. (https://doi.org/10.1029/2019JD030593)

Smith, D. M., Lopez, L. I., Lin, R. P., & Barrington-Leigh, C. P. (2005). Terrestrial gamma-ray flashes observed up to 20 mev. *Science*, *307*(5712), 1085-1088. (https://ui.adsabs.harvard.edu/abs/2005Sci...307.1085S)

Takahashi, T. (1978). Riming electrification as a charge generation mechanism in thunderstorms. *Atmospheric Sciences*, *35*, 1536–1548. (https://doi.org/10.1175/1520-0469(1978)035¡1536:REAACG¿2.0.CO;2)

Tsuchiya, H., Enoto, T., Iwata, K., Yamada, S., Yuasa, T., Kitaguchi, T., et al. (2013). Hardening and termination of long-duration γ rays detected prior to lightning. *Physical Review Letters*, *111*(1), 015001. (https://ui.adsabs.harvard.edu/abs/2013PhRvL.111a5001T)

Tsuchiya, H., Enoto, T., Yamada, S., Yuasa, T., Kawaharada, M., Kitaguchi, T., et al. (2007). Detection of high-energy gamma rays from winter thunderclouds. *Physics Review Letters*, *99*(4), 165002. (https://link.aps.org/doi/10.1103/PhysRevLett.99.165002)

Wada, Y., Bowers, G. S., Enoto, T., Kamogawa, M., Nakamura, Y., Morimoto, T., et al. (2018). Termination of electron acceleration in thundercloud by intracloud/intercloud discharge. *Geophysical Research Letters*, *45*(11), 5700-5707. (https://doi.org/10.1029/2018GL077784)

Wada, Y., Enoto, T., Nakamura, Y., Furuta, Y., Yuasa, T., Nakazawa, K., et al. (2019). Gamma-ray glow preceding downward terrestrial gamma-ray flash. *Communications Physics*, *2*(1), 67. (https://ui.adsabs.harvard.edu/abs/2019CmPhy...2...67W)

Wada, Y., Matsumoto, T., Enoto, T., Nakazawa, K., Yuasa, T., Furuta, Y., et al. (2021). Catalog of gamma-ray glows during four winter seasons in japan. *Physical Review Research*, *3*(4), 043117. (https://doi.org/10.48550/arXiv.2108.01829)

Wang, D., Wu, T., Huang, H., Yang, J., & Yamamoto, K. (2022). 3d mapping of winter lightning in japan with an array of discone antennas. *IEEJ Transactions on Electrical and Electronic Engineering*, *17*(11), 1606-1612.

(https://doi.org/10.1002/tee.23667)
Wu, T., Wang, D., & Takagi, N. (2018). Lightning mapping with an array of fast antennas. *Geophysical Research Letters*, *45*(8), 3698-3705. (https://doi.org/10.1002/2018GL077628)
Wu, T., Wang, D., & Takagi, N. (2020). Multiple-stroke positive cloud-to-ground lightning observed by the falma in winter thunderstorms in japan. *Geophysical Research: Atmospheres*, *125*(20), e2020JD033039. (https://doi.org/10.1029/2020JD033039)
Wu, T., Wang, D., & Takagi, N. (2022). On the intensity of first return strokes in positive cloud-to-ground lightning in winter. *Geophysical Research: Atmospheres*, *127*(22), e2022JD037282. (https://doi.org/10.1029/2022JD037282)
Wu, T., Yoshida, S., Akiyama, Y., Stock, M., Ushio, T., & Kawasaki, Z. (2015). Preliminary breakdown of intracloud lightning: Initiation altitude, propagation speed, pulse train characteristics, and step length estimation. *Geophysical Research: Atmospheres*, *120*(18), 9071-9086. (https://doi.org/10.1002/2015JD023546)
Yuasa, T., Wada, Y., Enoto, T., Furuta, Y., Tsuchiya, H., Hisadomi, S., et al. (2020). Thundercloud project: Exploring high-energy phenomena in thundercloud and lightning. *Progress of Theoretical and Experimental Physics*, *2020*(10), 103H01. (https://doi.org/10.1093/ptep/ptaa115)

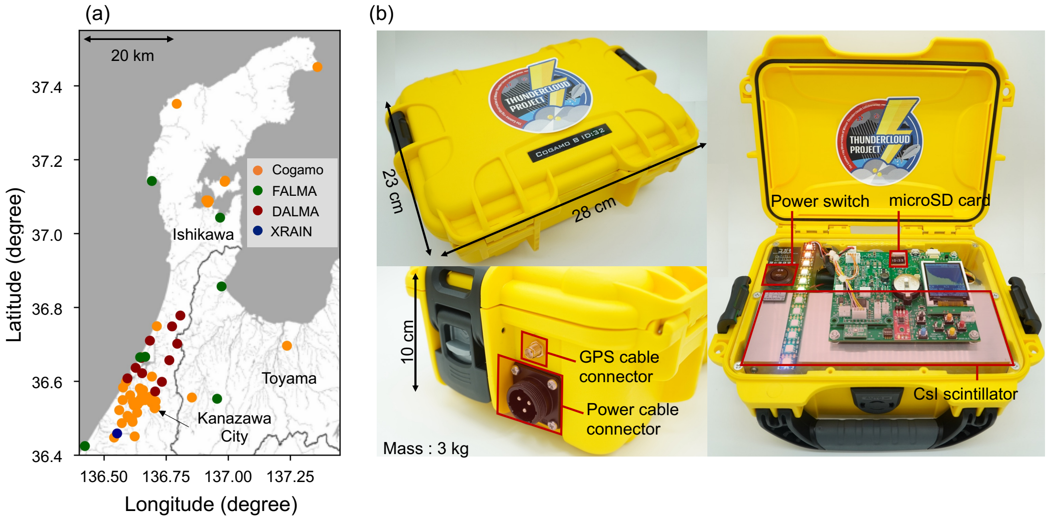

Figure 1. (a) Map of our observation sites in the Noto Peninsula. The orange, green, red, and blue circles show the locations of Cogamo detectors, the FALMA sites, DALMA sites, and the XRAIN Nomi Radar site, respectively. (b) Photographs of our portable Cogamo radiation detector.

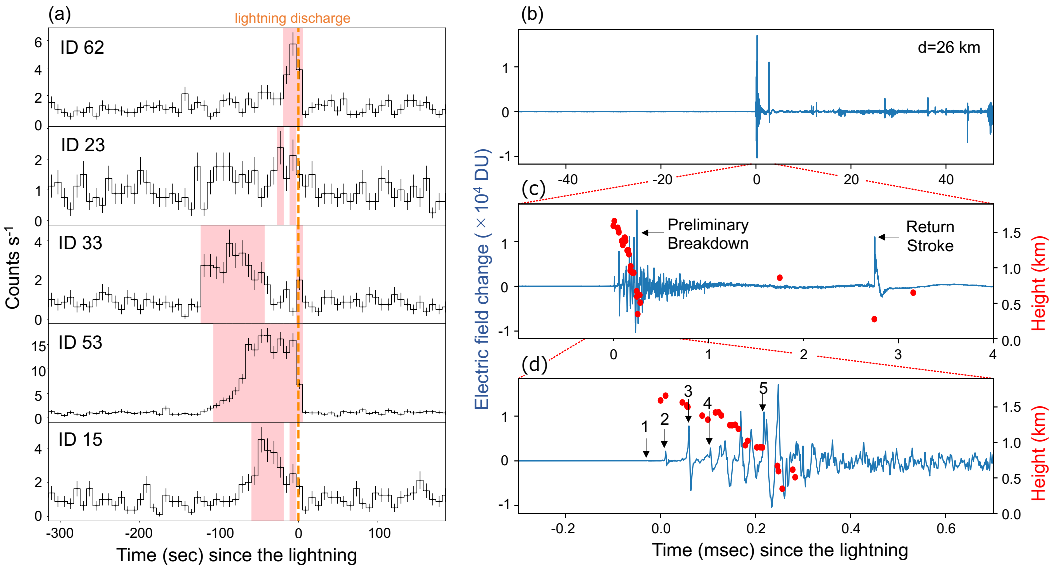

Figure 2. (a) 8-sec-binned count rate histories of radiation in the 3–10 MeV band recorded by five Cogamo detectors of, from the top to bottom panels, Cogamo IDs 62 (36.57N, 136.65E), 23 (36.57N, 136.65E), 33(36.56N, 136.65E), 53 (36.56N, 136.65E), and 15 (36.55N, 136.65E), in the order of the north to south. Error bars are statistical 1σ. The time origin is 04:08:34.8565 JST on 30 December, 2021, which corresponds to the first signal of the lightning discharge recorded by FALMA and DALMA. Data bins with detection significance exceeding 3.5σ are marked in red. (b–d) Preliminary breakdown pulses recorded by FALMA (blue lines, the left vertical axis) and their heights mapped by DALMA (red markers, the right axis). The time origin is the same as panel (a). The five pulses with numbers indicated are used for the location analysis.

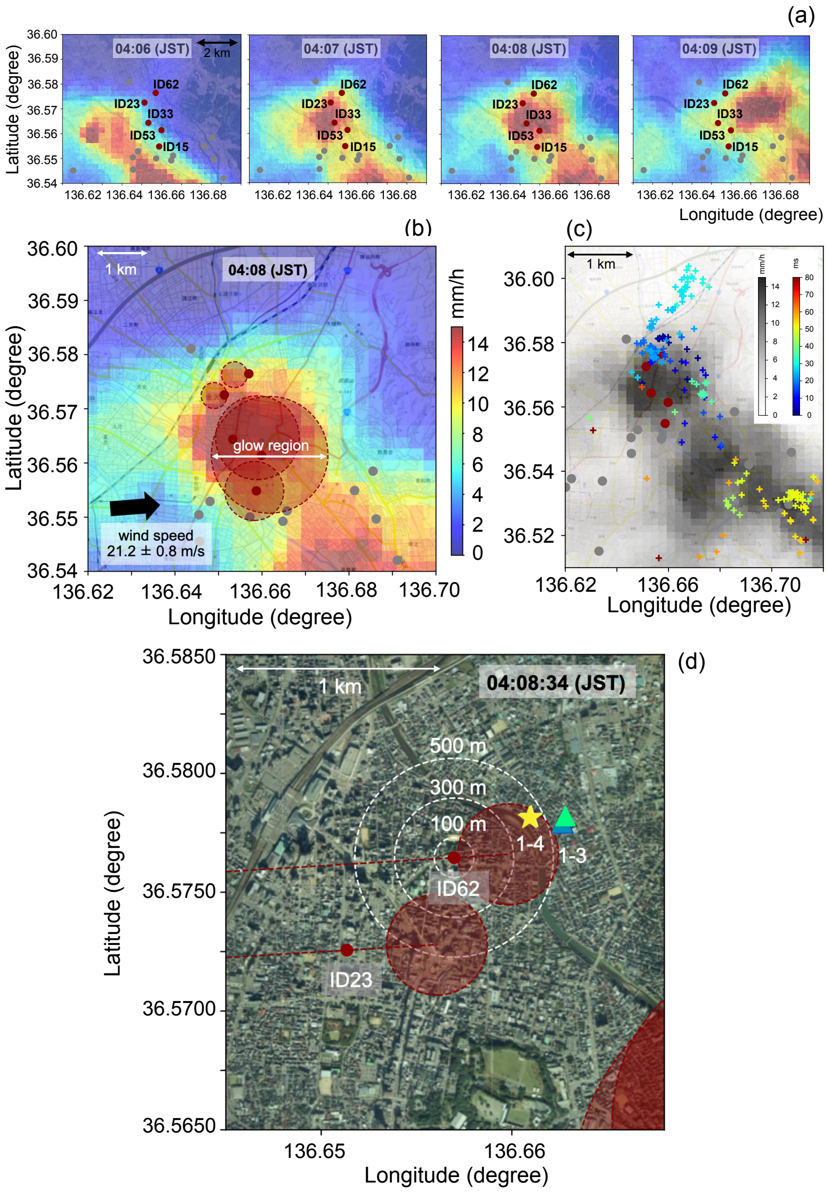

Figure 3. (a) XRAIN radar rainfall intensity maps in Kanazawa at every minute between 04:06–04:09 JST on 30 December, 2021. Locations of the Cogamo detectors are indicated in circle symbols, with their ID numbers. Red and gray circles show detectors with and without the gamma-ray glow detections, respectively, for the event reported in this paper. The overlaid topographic map is taken from the Geospatial Information Authority of Japan. (b) Same as panel (a) at 04:08 JST, but our estimated regions of gamma-ray radiation at individual Cogamo detectors are overlaid. The wind speed (21.2±0.8 m s^{-1}) and the direction of the westerly wind 266.5 degrees (clockwise with respect to the north) are also indicated. (c) Locations of lightning discharges (cross marks) detected by FALMA compared with the Cogamo locations (circle marks) and rainfall intensity (background in grayscale). The colors of the cross marks represent elapsed time of discharges from the time origin of 04:08:34.8565 JST (right-side color bar). (d) Zoom-up figure at 04:08:34 JST around the initial stage of the lightning flash. The lighting signals detected by FALMA and DALMA are indicated in star markers and triangles, respectively, with the numbers (1–4 and 1–3) corresponding to the orders of discharges (the first to the third signals and to the fourth signals). These signals indicate the starting position of the lightning discharges. The red marker is the Cogamo ID 62 location, and red-filled circles indicate the estimated gamma-ray glow regions at the timing of the lightning discharge.

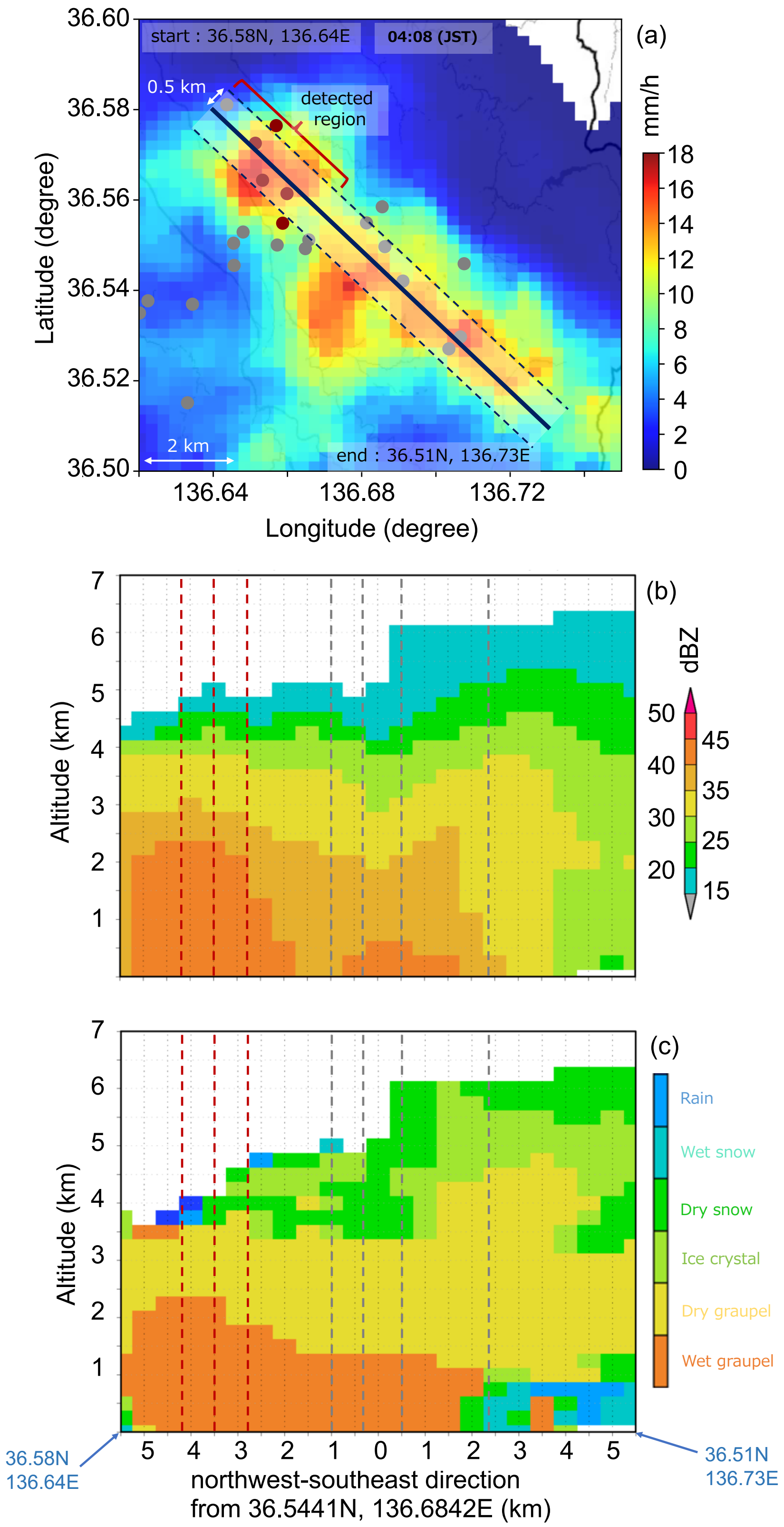

Figure 4. (a) Rainfall intensity map at 04:08 JST, the same as Figure 3 but showing a wider region. The blue solid line and dotted lines indicate the vertical cross-section to be used in panels b and c, and the distance of 500 m away from the cross-section, respectively. (b) Vertical cross-sectional view of the corrected reflectivity factor. Red vertical dotted lines and gray dotted lines indicate the locations of Cogamo detectors with and without gamma-ray detections, respectively, for the event within the 500 m region around the cross-sectional line. The central location is at (36.5441N, 136.6842E). (c) Same as Panel (b), but for the particle identification.