Difference between lightning activities in thunderstorm cells with and without hailfall in western Tokyo

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Abstract. Thunderstorm cells with heavy hailfall in Mitaka and Chofu on June 24, 2014, and in Koganei and Toshima on July 18, 2017, were investigated using data obtained from X-band multiparameter radar, ground-based atmospheric electric field, ground-based precipitation, and lightning location. For comparison, neighboring control cells with heavy rainfall but without hailfall were also investigated. The cells had a constant radius of approximately 10 km, and their centers were statistically obtained using the positions of positive and negative cloud-to-ground lightning (± CG). In both the target and control cells, the radar echo reflectivity, size, and updraft velocities after hailfall and heavy rainfall were similar, whereas the number of ± CG in the target cells was clearly smaller than that in the control ones. In contrast, the ice volume derived from the X-band multiparameter radar echo data in the target cells was greater than that in the control cells. Therefore, the large ice volume and the moderate number of ± CG were considered common features of cells experiencing hailfall.

Keywords: hailfall, thunderstorm, lightning, atmospheric electric field

1. Introduction

Electric charge is accumulated in a convective cloud because of the collision and friction between ice crystals (few μm to about 100 μm) and graupels (≤ 5 mm in diameter) during their updraft and downdraft. Graupels are formed when a graupel seed is lifted into a region of −20 °C by an updraft. While they are ascending and descending, the graupels further capture the surrounding supercooled water droplets and grow in size. Thus, they occasionally grow to form hail (> 5 mm in diameter). Hail is negatively and positively charged in regions cooler and warmer than −10 °C, respectively. This phenomenon leads to a corresponding negative and positive charge at the bottom of the thundercloud, respectively (Takahashi, 1978). Inside a mature thundercloud with lightning activities, the positively charged, lightweight ice crystals ascend to the upper
part of the cloud, the middle layer below $-10^\circ$C is negatively charged, and the lower layer is positively charged. This phenomenon is called a tripole structure. The tripole charged structure is formed in the mature thundercloud (Takahashi, 1978). In addition, when the gravitational force exerted on the graupels and hail exceeds the updraft force, they fall to the ground, resulting in hailfall and rainfall.

Figure 1. The analyzed zone in the Kanto Plain. The atmospheric electric field (AEF) observations (brown inverted triangle) were obtained at Koganei (KGN), Musashino (MSN), Mitaka (MTK), and Chofu (CHF). The Tateno aerological observations were conducted in Tsukuba (blue square), Ibaraki Prefecture (TAO). The X-band multi-parameter (MP) radars (red stars) were operated at the Funabashi (FNB), Shinyokohama (SYK), and Kanto (KNT) stations. The precipitation (black inverted triangle) was observed at Nukui (NKI; 400 m south of KGN), Tsujido (TJD) data were provided by the Automated Meteorological Data Acquisition System operated by the Japan Meteorological Agency (JMA), Mitaka (MTK), and Imajuku (IMJ) were operated by the local government. The solid red and black lines represent the hailfall areas of 2014 events reported by Shusse (2014) and 2017 events estimated by our study, as shown in the Appendix.

On June 24, 2014, the Baiu rain front was elongated to the south of $30^\circ$N, far from the south coast of the Kanto Plain, and an upper cold trough was located above the Kanto Plain, making the atmospheric conditions extremely unstable (Hayashi, 2015; Hayashi et al., 2015). A heavy hailstorm with severe lightning and strong winds occurred in Chofu and Mitaka, western Tokyo (Figure 1), at approximately 14:30 JST (JST = UTC + 9:00), 60 minutes after the C-band composite radar echo at an altitude of 2 km was first observed. According to a field survey report (Shusse, 2014), the hailstone diameter was greater than 3 cm, and the hailstone was alternately stratified by an opaque layer.
comprising several bubbles and a transparent layer comprising a few bubbles. This implies that the hailstone grew because of the repeated capture of supercooled water droplets and because of the repeated collision and friction inside the cloud while melting when descending and refreezing when ascending (Shusse, 2014).

On July 18, 2017, atmospheric conditions became extremely unstable because of the continuous inflow of cold air in the middle troposphere above the Kanto Plain, as reported by the Japan Meteorological Agency (JMA). Heavy rain and lightning warnings were issued by the JMA for certain areas of Tokyo and Kanagawa Prefecture. A heavy hailstorm occurred at approximately 14:00 JST in Koganei (Iwai et al., 2018) and at approximately 15:00 JST in Toshima/Bunkyo, with severe lightning and strong winds in western/central Tokyo, according to numerous weather reports on the internet (Hailfall database, National Research Institute for Earth Science and Disaster Prevention; https://mizu.bosai.go.jp/wiki2/, Last Search Date: May 12, 2021) (Figure 1). The hailfall region migrated eastward from Koganei to Toshima/Bunkyo in Tokyo, which lasted approximately 90 minutes in total. The area survey of hailfall on the ground in this event is described in the Appendix.

This simultaneous occurrence of extreme weather and lightning might be closely related. The occurrence of lightning is considered a tool for surveying and predicting severe weather (Price, 2013). Hailfall is strongly associated with thunderstorms, which are one of the major concerns of lightning application research in atmospheric electricity and meteorology. In this study, two hailfall events on June 24, 2014, and July 18, 2017, were analyzed to highlight the electrical and meteorological differences between hailstorms and heavy rainstorms associated with lightning activity.

| Observation item | Location                      | Station information |
|------------------|-------------------------------|---------------------|
| **X-band multi-parameter radar echo** | Funabashi, Chiba | FNB 35.6958° N 140.0072° E |
|                  | Shinyokohama, Kanagawa       | SYK 35.5125° N 139.5994° E |
|                  | Kanto, Saitama               | KNT 35.8908° N 139.6339° E |
| **Precipitation** | Nukui, Koganei, Tokyo        | NKI 35.69744° N 139.49134° E |
|                  | Tsujido, Fujisawa, Kanagawa | TJD 35.32108° N 139.44851° E |
|                  | Mitaka, Tokyo                | MTK 35.68060° N 139.56803° E |
|                  | Imajuku, Yokohama, Kanagawa | IMJ 35.47328° N 139.51867° E |
| **Atmospheric electric field** | Koganei, Tokyo | KGN 35.70535° N 139.49040° E |
|                  | Musashino, Tokyo             | MSN 35.71619° N 139.57254° E |
|                  | Mitaka, Tokyo                | MTK 35.68070° N 139.55810° E |
|                  | Chofu, Tokyo                 | CHF 35.67455° N 139.53007° E |
| **Aerological temperature** | Tateno, Tsukuba, Ibaragi    | TAO 36.0583° N 140.1250° E |
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Figure 2. X-band MP radar reflectivity at an altitude of 2 km at (a) 14:30 JST (target) and (b) 12:40 JST (control) on June 24, 2014, and (c) 14:10 JST (target) and (d) 14:00 JST (control) on July 18, 2017. Open and solid triangles, open and solid circles, and open and solid squares indicated at the top right of the panels denote positive and negative cloud-to-ground lightning (± CG) for 10 min, as identified by the Environmental Sensor Network (ESN) (green), Japan Lightning Detection Network (JLDN) (blue), and Lightning Detection Network system (LIDEN) (purple), respectively. Green, blue, and purple dashed circles of a 10 km radius are centered at the median of the ± CG location, as identified by ESN, JLDN, and LIDEN, respectively.
2. Observation and Analysis

We used X-band multiparameter (MP) radar echo data to investigate thunderstorm cells. The X-band MP radars obtained echo data at the Funabashi, Shinyokohama, and Kanto stations operated by the Ministry of Land, Infrastructure, and Tourism in Japan (Figure 1 and Table 1). In the analysis, we identified cells with hailfall and cells with only heavy rainfall as the target and control cells, respectively. The target and control cells were considered similar in terms of their size and X-band MP radar echo reflectivity. The control cell, which is shown in the analyzed zone in Figure 2, was selected as the spatiotemporally adjacent target cell. To identify the cells from the X-band MP radar echo data, we constructed composite X-band MP radar echo data of the target and control areas on both hailfall days. The composite data were fabricated based on the data of the three stations because one X-band MP radar could not detect the entire structure of the active thunderstorm due to the strong attenuation of the radar waves. In this study, the composite process corresponded to the largest value of horizontal reflectivity in each grid of the three X-band MP radar echo data.

To follow the migrating cells and investigate their features, the analysis circles containing the cells were selected every five minutes using the lightning location data. For simplicity of analysis, the analysis circle had a constant radius of 10 km, as shown in Figure 2. The median of the latitude and longitude of the ± CG within ± 5 minutes at the time of the X-band MP radar echo was derived for the center point of the target and control areas using the lightning catalogue inside the 30-km radius circle (see the black solid line for June 24, 2014, and the black solid and dashed lines for July 18, 2017, in Figure 3). Figure 3 shows the migrating analysis circles of the target and control cells on June 24, 2014, and July 18, 2017.

Three sets of lightning location catalogues were provided by the ESN (Moriyama et al., 2016) operated by NTT DOCOMO Co. Ltd. (Tsuboya et al., 2016), the JLDN (Ishii et al., 2005; Matsui et al., 2016) operated by Franklin Japan Co. Ltd., and the LIDEN operated by the JMA (Ishii et al., 2014). These catalogues were employed on June 24, 2014, to avoid a catalogue dependence and to confirm catalogue accuracy because of the small number of lightning occurrences, which caused a statistically large fluctuation. In contrast, only the JLDN was used on July 18, 2017, because the lightning number was large. The ESN, JLDN, and LIDEN data provided the occurrence time with 1 s, 1 μs, and 100 μs time resolutions, respectively, type (i.e., intra/inter-cloud lightning or ± CG), peak current, position, and polarity of lightning. Figures 4 and 5 show the time series of the number of ± CG lightning, the total peak current, and the average of the peak current every 10 minutes inside the analysis circles of the target and control cells on June 24, 2014, and July 18, 2017, respectively.

To discuss the time series of the height profile of the X-band MP radar reflectivity and lightning number variations inside the target and control cells, the X-band MP radar reflectivity was evaluated at every 1 km altitude within a 0.5 km radius from the calculated center of the analysis circle, the number of ± CG for 10 min, the sum of peak current in ± CG, and the median of peak current with interquartile range as error bars (only for JLDN) in ± CG in the target and control areas.
We analyzed the particle components of the cell from the X-band MP radar echo data, such as the presence of graupels/hailstones and raindrops inside the cell. In particular, the hailstones and raindrops can be distinguished using empirical formulae based on radar reflectivity $Z_e$ [dBZ] and the specific differential phase shift $K_{DP}$ [$°/km$] (Balakrishnan et al., 1990). A large raindrop becomes more ellipsoidal in shape over time. In other words, the $K_{DP}$ logarithmically increases when $Z_e$ increases (Doviak et al., 2006). In contrast, $K_{DP}$ remains constant at nearly zero when $Z_e$ increases because the hail maintains its spherical shape as it grows. Therefore, the following simplified relationship was obtained by adjusting the empirical formulae to differentiate rain from hail based on the observations (Balakrishnan et al., 1990; Doviak et al., 2006):

$$Z_e > 8 \log (2 \cdot K_{DP}) + 49$$  \hspace{1cm} (1).

By applying Equation (1) to the observed $Z_e$ and $K_{DP}$ values at each grid, the ice volume [km$^3$] was derived from the total grid number of hail within an arbitrary volume. In the present analysis, we calculated the volume of the cylindrical column with a 20 km radius and 1 km height, corresponding to a volume of 1256 km$^3$ at an altitude of every 1 km. The center of the cylinder with a 20 km radius for the ice volume was obtained as an average of the median values derived from the 10-minute ± CG lightning location every five minutes during the analysis period in both the target and control areas on both hailfall days. Figures 6a and 7a show the time series of ice volume in the target and control areas on June 24, 2014, and July 18, 2017, respectively.

To observe the precipitation on the ground in the target and control areas, the study used precipitation data obtained at Nukui, Koganei, Tokyo (NKI; 0.4 km south of KGN), and Tsujido, Fujisawa, Kanagawa Prefecture (TJD) provided by the Automated Meteorological Data Acquisition System operated by the JMA, at Mitaka, Tokyo (MTK), and Imajuku, Yokohama, Kanagawa Prefecture (IMJ) operated by the local government (see Figure 2 and Table 1). Figures 6b and 7b show the time series of precipitation in the target and control areas on June 24, 2014, and July 18, 2017, respectively.

The atmospheric electric field (AEF) was observed using an electric field mill (FM) installed at Koganei (KGN) on June 24, 2014 (Figure 1 and Table 1), and Musashino (MSN), Mitaka (MTK), and Chofu (CHF) on July 18, 2017 (Figure 1 and Table 1). The downward direction of the vertical AEF from the ionosphere to the ground was defined as positive. When the negatively charged region of the thundercloud bottom was just above the FM, the observed AEF polarity was found to be negative. The lightning resulted in a sharp spike-like AEF waveform. To analyze the charged structure inside the thunderstorm cell, the time series of the AEF was used. In general, the AEF was amplified by the characteristics of the measurement site, such as installation height and surrounding topography. The data must be calibrated to remove the effects of the installation height and the surrounding topography. Data calibration on the ground in fair weather was not performed for the hailfall event on June 24, 2014. In contrast, calibration was performed at the three measurement sites for the hailfall event on July 18, 2017. Figures 8 and 9 show the time series of AEF and the distance from the center point of the analysis circle to the AEF observation point to investigate the detectable distances of the thunderstorm origin AEFs on June 24, 2014, and July 18, 2017, respectively.
Dual-doppler analysis using two X-band MP radar echo stations at Kanto and Funabashi was performed to calculate the updraft velocity in the cells and the vertical average of the updraft velocity per 1 km² (horizontal area). In this study, the calculated area for the dual-doppler analysis was 20 km², the center of which was obtained as the average of the medians derived from the 10-minute ± CG lightning location every five minutes during the analysis period in both the target and control areas on both hailfall days (Figures 10 and 11).

Aerological observation data from Tateno Aerological Observatory Tsukuba, Ibaragi Prefecture (TAO; Figure 1), provided by the JMA, which was the nearest aerological observation point from the target and control areas, were used. The aerological observation data obtained at Tateno, at −10 °C altitude, which produced the negatively charged hail/graupel, were obtained at approximately 5.6 km at 09:00 JST on June 24, 2014, and 6.2 km at 09:00 JST on July 18, 2017. In addition, the 0 °C altitude for melting the hail/graupel is shown.

Dual-doppler analysis was conducted at Kanto and Funabashi using the two-station data of the X-band MP radar echo, which provided the average velocity of updraft and downdraft from 1 km to 15 km altitude per 1 km². The analysis area was 40 km², the center of which corresponds to the average location of the center of the migrating analysis circles. Figures 10 and 11 show the updraft velocities for 20 minutes before and after hailfall and heavy rainfall started on June 24, 2014, and July 18, 2017, respectively.

3. Results and Discussion
3.1. Hailfall Event on June 24, 2014

On June 24, 2014, the onset time of hailfall in the target cell reported by the field survey (Shusse, 2014) was 14:30 JST (Figure 2a). The X-band MP radar reflectivity, Ze, at an altitude of 2 km in the target and control areas was obtained after 14:00 JST and 12:10 JST, respectively. The onset time of the widely covered heavy rainfall was 12:40 JST (Figure 2b). In this study, the heavy rainfall shown in the brown dotted bar of Figure 4a was defined as when precipitation with 50 mm/h was widely observed on the ground. In addition, the onset time of the heavy rainfall was defined when the total area of Ze > 30 dBZ at the altitude of 2 km in the target and control areas at the onset time of the hailfall was the same (allowing ± 10% difference) and the sum of Ze at the altitude of 1–10 km in the altitude was the same (allowing ± 15% difference). Note that the onset time of heavy rainfall was not the onset time of rainfall. In the following analyses, we assumed that the centers of the target and control cells before 14:30 and 12:40 JST had the same center at 14:30 and 12:40 JST, respectively, because the number of ± CG was not enough to evaluate the centers.

As shown in Figures 4b–d, the time series of the number of ± CG and their total and median peak current values in the three lightning catalogues showed roughly similar trends, except for the + CG data obtained by LIDEN, in which the total and median peak currents (shown in Figures 4c and 4d) fluctuated—probably because the detected number of ± CG was small. Therefore, the ESN and JLDN catalogues were employed for our analysis.
Figure 3. Areas of the lightning catalogue to evaluate the centers of the cells are represented by black solid and dashed circles (30 km radius). The analyzed area, including the cell corresponding to the analysis circle every five minutes, is shown by the colored solid (target) and dashed (control) circles (10 km radius), which indicate the temporal migration of the cell. The gray solid and dashed circles denote the calculation area for the ice volumes in the target and control areas, respectively. This figure uses only JLDN data. The time sequence of migrating cells shows the graduated color circles (cool color: early; warm color: late).
Figure 4. The time series of the hailfall event on June 24, 2014. The area shaded in blue represents the hailfall period. The dashed vertical brown line denotes the start of heavy rainfall. The horizontal red and black dotted lines denote the −10 °C and 0 °C altitudes in Tateno, respectively. (a) Reflectivity ($Z_e$), (b) number of ± CG for 10 minutes (the green, blue, and purple lines denote ESN, JLDN, and LIDEN, respectively), (c) the sum of peak current in ± CG, and (d) the median of peak current with interquartile range as error bars (only for JLDN) in ± CG in the target (left column) and control (right column) areas. The count of + CG was selected to exclude the incorrect identification of intracloud lightning when the peak current was more than 10 kA in accordance with Ishii et al. (2005).
Figure 5. The time series of the hailfall event on July 18, 2017. Same as Figure 4, except that the hailfall event on July 18, 2017, is shown.
Figure 6. The time series of the hailfall event on June 24, 2014. The area shaded in blue represents the hailfall period. The dashed vertical brown line denotes the start of heavy rainfall. The horizontal red and black dashed lines denote the −10 °C and 0 °C altitudes in Tateno, respectively. (a) Time series of graupel/hail volumes, (b) and precipitation measured on the ground in the target (left column) and control (right column) areas.

Figure 7. The time series of the hailfall event on July 18, 2017. Same as Figure 6, except that the hailfall event on July 18, 2017, is shown.
The height profile of the reflectivity and the number of $-$ CG in the target and control areas began to increase with an increase in precipitation around 14:00 and 12:20 JST, respectively, and slightly decreased around 30 min later (Figures 4a and 4b), while hailfall and rainfall monotonically increased from 14:20 and 12:30 JST to 15:00 and 13:30 JST, respectively (Figure 6b). This implies that the precipitation probably led to the loss of negatively charged hailstones and raindrops present at the bottom of the cell, resulting in the suppression of $-$ CG occurrences (Figure 4b). The precipitation was roughly similar in both the target and control areas (Figure 6b). In contrast, the ice volume in the target area was larger than that in the control area, as can be clearly observed in Figure 6a.

The number of $-$ CG in the control area was higher than that in the target area. The total peak current (i.e., the summation of the $\pm$ CG peak current for 10 minutes) in the target and control areas was proportional to the number of $-$ CG, as shown in Figure 4c. Figure 4d shows that the median peak current of $-$ CG was almost constant for 10 minutes. In contrast, the number of $+$ CG was much smaller than that of $-$ CG even in the ENS and JLDN catalogues: thus, the features of the number of $+$ CG, which fluctuated, were not discussed for this event.

As shown in Figure 8a, the AEF gradually changed from positive to negative at approximately 14:15 JST. This indicates a gradual accumulation of negative charges at the bottom of the target cell. In addition, the AEF at the time of hailfall, i.e., at 14:30 JST, abruptly became significantly negative. This implies the accumulation of negatively charged hail at the bottom of the thundercloud. Subsequently, the polarity of the AEF gradually changed from negative to positive at approximately 14:45 JST, suggesting that the negative charge at the bottom of the thundercloud may have been removed owing to the negatively charged hailfall, changing the net charge of the thundercloud from negative to positive.

The polarity of the AEF was affected by the distance between the FM and the thundercloud. Based on the two lightning catalogues (ESN and JLDN), the distance between the center of the target cell and the FM at KGN remained constant at approximately 10–13 km from 14:30 to 15:00 JST, that is, during the hailfall period (Figure 8b). Thus, the change was the polarity of the AEF from positive to negative at around 14:30 and from negative and positive at around 14:45, which were regarded as changes in the net charge of the target cell. Notably, the similar polarity changes before and after 15:10 were caused by the approach of a different cell.

The results of the dual-doppler analysis shown in Figure 10 indicate that the average velocities of updraft and downdraft per 1 km$^2$ around the target area were higher than those in the control area. From the X-band MP radar reflectivity at an altitude of 2 km, as well as the data from two lightning catalogues, we found that the target cell slowly migrated eastward from 14:10 to 14:30 JST and then northward from 14:30 to 14:50 JST (Figure 3). The updraft region was widely distributed before the hailfall in the target area from 14:10 to 14:30 JST, as shown in Figure 10a. However, the updraft region was concentrated in the area where hailfall was observed from 14:30 to 14:50 JST, as shown in Figure 10c (Shusse, 2014), whereas the downdraft region occurred around the
hailfall area where hailfall was observed. In contrast, the updraft and downdraft in the control area were less active than those in the target area, as shown in Figures 10b and 10d. In particular, the contrast between the updraft and downdraft velocities in the target area was sufficiently clearer than that in the control area.

![Figure 8. Time series of the hailfall event on June 24, 2014. The area shaded in blue represents the hailfall period. AEF observations at KGN were located below the target cell. (a) The solid line shows the raw data (red) and running median (blue) for ± 2 min at KGN. Note that the AEF is expressed with an arbitrary unit because the measurement was not calibrated. (b) The lines show the distance from the center points of the target cells to the KGN using the ESN and JLDN lightning catalogues.](image)

### 3.2. Hailfall Event on July 18, 2017

Similar analyses were conducted as detailed in Section 3.1. On July 18, 2017, the onset time of hailfall in the target cell was 14:00 JST around Koganei (very close to KGN), Tokyo (Figure 2c: Iwai et al, 2018). The onset time of heavy rainfall in the control cell was 14:00 JST, following the same criteria as the event on July 24, 2014.

Notably, only the JLDN catalogue was used because the ESN was not under operation at the time and enough ± CG were obtained to provide a detailed statistical analysis, which was different from the analysis using the number of + CG on June 24, 2014. The number of ± CG reached the peak value slightly after the onset time of hailfall and heavy rainfall in the target and control areas. In the target area, the clear peak of the
number of − CG at 14:05 JST was 10 minutes earlier than that of the number of + CG at 14:15 JST (Figure 5b). As noted during the event on June 24, 2014, the hailstones carried the negative charge to the ground, which decreased the number of − CG. We inferred that this decrease promoted the number of + CG originating from the remaining positive charges (probably located in the upper part of the thundercloud), delaying the peak of + CG by ten minutes. In contrast, a five-minute difference was observed between the peaks of the number of ± CG in the control area (Figure 5b). The median peak currents (Figure 5d) in the target and control areas remained constant before and after the peaks of the number of ± CG.

The target area had higher ice volumes at lower altitudes and for longer durations than the control area (Figure 7a). This was also observed for the hailfall event that occurred on June 24, 2014. The ice volume on July 18, 2017, was approximately three times larger than that of June 24, 2014, at low latitudes. The largest ice volume (around 40 km³) on June 24, 2014, was located at an altitude of approximately 5 km corresponding to −10 °C, whereas the largest ice volume (more than 120 km³) on July 18, 2017, was located at an altitude below around 6 km corresponding to −10 °C, which might indicate the existence of hail and melting hail precipitation. The ice volume before the hailfall at 14:10 JST in the target area was larger and wider (around 50 km³) than the ice volume before the heavy rainfall at 14:00 JST in the control area.

Figure 9a shows the AEF variation caused by thunderstorm electricity at the three stations in the target area. The detectable distance between the FMs at the three stations and the center of the cell derived by the JLDN data was approximately 25 km (Figure 9b) because the AEF variations diminished at approximately 15:20 JST, although the cells in the target area were migrating eastward. From 13:20 to 14:05 JST, before the hailfall started in the target area, the reflectivity (Figure 5a) and the ice volume (Figure 7a) increased at an altitude of approximately 5–10 km, and the negative electric field dominated. This means that negatively charged hail and graupel were generated at an altitude of 5–10 km. After hailfall started, the polarities of the AEF were found to oscillate at the three stations. We inferred that the negatively charged hailfall led to the positive polarity of AEF, as observed on June 24, 2014, and that the negative charge regeneration at the bottom of the cell, leading to the negative polarity of AEF in the target area, recurred.

Figure 11 shows the vertically averaged updraft and downdraft velocities per 1 km² on July 18, 2017. In both the target and control areas (gray solid and dotted squares shown in Figure 11, respectively), active updraft and downdraft were clearly observed before/after hailfall and heavy rainfall, respectively. In other words, there was no significant difference between the vertically averaged velocities in the target and control areas. In the target area, after hailfall (Figure 11c), the intense updraft velocity region in the northwest part of NKI (around KGN) was large and widespread, where hailfall was observed at approximately 14:10 JST (Iwai et al., 2018).
Figure 9. Time series of hailfall on July 18, 2017. The blue-shaded area represents the hailfall period. The three AEF observation points were located below the target area. (a) The solid lines show the running median for ± 2 min at the three points of the field mill (FM) observation. (b) The lines show the distance of the center points of the target cells from the three points of FM observation.
Figure 10. Vertically averaged velocities of updraft and downdraft in a square of 1 km × 1 km from altitudes of 1 km to 15 km on June 24, 2014. The solid and dashed gray squares (20 km × 20 km; the center corresponds to the center of the solid and dotted gray circles shown in Figure 3) represent the areas studied by dual-doppler analysis. The solid dashed lines in the target areas denote the hailfall region surveyed by Shusse (2014).
Figure 11. Vertically averaged velocities of updraft and downdraft in a square of 1 km × 1 km from altitudes of 1 km to 15 km on July 18, 2017. The same as in Figure 10, except that the hailfall event on July 18, 2017, is shown.
4. Conclusion

The thunderstorm cells observed at two hailfall events occurred in similar places in western Tokyo were analyzed. In the target (with hailfall) and control (without hailfall) cells, the number of ± CG monotonically increased prior to the charged hail/graupel led to a loss of the net charge of the cell, which caused a reduction in the CG.

Moreover, for the two events of 2014 and 2017, the cell sizes were roughly the same, although the number of ± CG in the hailfall event of 2017 was overwhelmingly larger than that in the hailfall event of 2014. Based on the two events and a comparison between the target and control cells, the following common features were inferred: 1) The number of ± CG in the case with heavy rainfall without hailfall was larger than that in the case with hailfall, and 2) the ice volume in the case with hailfall was larger than that in the case without hailfall.

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**Appendix**

The hailfall area on July 18, 2017, has not been investigated, as shown in Shusse et al. (2014). Therefore, based on the information available on news and on the Internet, the spatio-temporal hailfall features were investigated (Figure A1 and Table A1). Hailstones with a diameter of about 1 cm were observed in Koganei, western Tokyo, from 14:00 to 14:15 under the thunderstorms (Iwai et al., 2018) [1]. Then, at around 15:00, the hailfall area migrated westward and was found at Nerima [2], Toshima [3], Kita [4], and Bunkyo [5]. The last report was that the hailfall was seen at 15:30 in Arakawa [6] and Taito [7]. The diameter of the hailstones was occasionally found to be in excess of 5 cm at these central Tokyo [7].

The hailfall area systematically estimated from X-band radar (National Research Institute for Earth Science and Disaster Prevention: NIED) is also shown in Figure A1 [8]. In this estimation, the $dR$ intensity was obtained by subtracting the rainfall intensity...
calculated from $K_{DP}$ from the rainfall intensity calculated from $Ze$ at an altitude of 1 km. The hailfall area was eventually defined as the area where the $dR$ intensity was high. In Figure A1, the high $dR$ at 15:10 was shown as a probable hailstorm area. In this paper, we regard a region with $dR$ more than 20 mm/h as the hailfall area.

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Table A1. Reported hailfall location, time, and references for July 18, 2017 event.

| Location number in Figure A1 | Eyewitness | Time (Period) | References |
|-----------------------------|------------|---------------|------------|
| ①                          | Koganei    | 14:00–14:15   | Iwai et al. (2018) [1] |
| ②                          | Nerima     | Around 15:00  | [2]        |
| ③                          | Toshima    | Around 15:00  | [3]        |
| ④                          | Kita       | Around 15:00  | [4]        |
| ⑤                          | Bunkyo     | Around 15:14  | [5]        |
| ⑥                          | Arakawa    | Around 15:30  | [6]        |
| ⑦                          | Taito      | Around 15:30  | [7]        |
Figure A1. Reported hailfall locations (①-⑦) and the dR (> 20 mm/h) area at 15:10 [8] on July 18, 2017.