Charge Regions Indicated by LMA Lightning Flashes in Hokuriku’s Winter Thunderstorms

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Abstract The charge distribution of some cells in three winter thunderstorms in the Hokuriku region of Japan is investigated based on Lightning Mapping Array (LMA) flash data. The vertical arrangements of charge regions involved in lightning discharges suggest diverse charge patterns, including quad-polar, tripole, positive dipole, inverted dipole, and inverted tripole. The riming electrification between graupel and ice crystals or their aggregations are thought to be responsible for the electrification of most cells. The charging process between snow/aggregates and ice crystals may be responsible for some inverted charge structure that occurred above 0 °C isotherm and accompanied with weak radar echoes. Convection indicated by the vertical development of radar reflectivity appears crucial to shaping the diverse charge distribution patterns by determining which charging mechanisms occur and where; it also influences changes in height or even the disappearance of the charge regions. The charged cores are distributed from 0.7 to 5.3-km heights and 2 to 31 °C temperatures, while the distances between adjacent charged cores with opposite polarities change between 0.2 and 3.4 km, with a mean of 1.3 km. The mean flash duration and horizontal distance are 425.0 ms and 19.8 km, respectively. The average height, temperature, and power of flash initiations are 2.8 km, −11.9 °C, and 15.6 dBW, respectively.

1. Introduction

The coastal areas of Japan are hot spots of thunderstorms and lightning activities in winter, because warm oceanic water beneath colder air produces energy for convection (Ishii et al., 2014; Montanyà et al., 2016). The charge structure plays a crucial role in determining the characteristics of lightning and, therefore, gets special interest. Most previous studies have suggested that Japanese winter thunderstorms have normal charge structures similar to summer thunderstorms (i.e., a positively charged region above a negatively charged region (dipolar structure) and possibly an additional positively charged region at the lower level (triplar structure); e.g., Brook et al., 1982; Kitagawa & Michimoto, 1994; Takahashi et al., 1999, 2017, 2018; Yoshida et al., 2018). Takahashi et al. (1999, 2018) described the charge evolution in Hokuriku winter clouds. When a cloud starts to develop, droplets grow and freeze at temperatures smaller than −10 °C, forming the seeds of graupel particles. According to the riming electrification mechanism (Takahashi, 1978), collisions between graupel particles and ice crystals make graupel become negatively charged and ice crystals positively charged. Positive ice crystals are transported by the updraft to the upper layer of cloud. At temperatures above −10 °C, graupel particles gain positive charges, and ice crystals gain negative charges when they collide with each other (Takahashi, 1978). During the mature stage, these negative ice crystals are joined by negative graupel particles at midlevel, causing the accumulation of negative charges. During the dissipation stage, the downdraft throughout the cloud depth causes the positive ice crystals to descend from the cloud top to join the positive graupels at the warm-temperature level, strengthening the positively charged region at the bottom. In addition, the heights of the charge regions in winter thunderstorms are universally lower than those in summer thunderstorms, but their corresponding temperatures are analogous to those in summer thunderstorms (e.g., Krebsbiet, 1986; Morimoto et al., 2005; Takahashi et al., 1999, 2017, 2018; Yoshida et al., 2018).

Typical methods analyzing the charge structure of winter storms in Japan include estimating the magnitude and equivalent core location of charges transferred by cloud-to-ground (CG) lightning using a point charge model based on measurement of the electric field changes caused by CG lightning at multiple sites (e.g.,
Brook et al., 1982; Ishii, 2003) and measuring the precipitation particle-type, charge and cloud water content using videosonde (e.g., Takahashi et al., 1999, 2017, 2018). In recent years, 3-D lightning detection technology has provided a valid method to infer charge regions by mapping the radiation sources of lightning channels. Compared to the aforementioned methods, an obvious advantage of this method is that it has the potential to infer the charge distribution of the entire electric thunderstorm. In recent years, Kumjian and Deierling (2015), Caicedo et al. (2018), and Schultz et al. (2018) employed lightning radiation source data from the Lightning Mapping Array (LMA), a 3-D lightning location system running at a very high frequency, to infer the charge structures of winter/spring storms in several U.S. regions, including Colorado, Florida, Alabama, Oklahoma, and Washington DC. The dipolar or tripolar charge distributions were suggested in their studies. However, investigating the charge distribution using lightning radiation sources in Japanese winter storms is still relatively new. There are several statistical works that have analyzed the height distribution of the number of lightning flash sources to roughly indicate the height range of charge regions (e.g., Ishii, 2003; Morimoto et al., 2005; Yoshida et al., 2018). For instance, Ishii (2003) indicated two positive charge layers around −10 and −30 °C, respectively, according to the statistics on 68 flashes in Fukui’s winter storms; Morimoto et al. (2005) observed that the central altitude of very high frequency sources in the winter storms indicated by the broadband interferometer was about 2.5 km in Fukui, Japan; and Yoshida et al. (2018) found that the altitude of winter flash sources observed by a low-frequency lightning location network (230−500 kHz after applying a band-passed digital filter) peaked at 2.1 km or near −10 °C in the Japanese Shonai area. However, these studies did not identify the breakdown polarity of channels in each flash, which is important to get the detailed charge distribution through the thunderstorm.

During the winter of 2014, a nine-station LMA was set up in the Hokuriku region of Japan (see Figure 1) with the aim of observing 3-D lightning discharges in winter. Wang et al. (2018) performed a preliminary analysis on the charge structures in winter thunderstorms on 14 November 2014 and suggested that the distributions of the charges involved in the lightning discharges were diverse. In this study, we also employ the

![Figure 1. The locations of the substations of the Lightning Mapping Array (LMA), Fukui radar, and Wajima sounding shown over terrains colored according to the altitude above sea level.](image-url)
observations of this LMA but focus on a total of 3 days of winter thunderstorms, which are associated with the charge discharges with specific cells. This study provides us with new knowledge on the charge regions in Hokuriku's winter storms.

2. Data and Methodology

2.1. Observation and Data

During the winter of 2014, a nine-station LMA was first deployed in the Hokuriku region of Japan (Figure 1). This LMA was combined with Fukui radar and Wajima sounding (Figure 1) to provide 3-D flash observations, radar echoes, and atmospheric isotherms in three thunderstorms occurring on 12 and 14 November and 2 December 2014, respectively. The CG lightning flashes observed by the Japanese Lightning Detection Network during the same time were also referenced.

The LMA located flash breakdown events using time of arrival technology, with a reported uncertainty of 6- to 12-m root-mean-square in the horizontal and 20- to 30-m root-mean-square in the vertical (Krehbiel et al., 2000; Rison et al., 1999; Thomas et al., 2004). When checking the data, it was found that the location accuracy of the LMA was reduced obviously over a long distance, which we speculate was at least partly due to the relatively short baseline and generally low altitude of the lightning in winter thunderstorms. Regardless of the situation, to ensure the reliability of the data, we chose a circular centered on the LMA station centroid (average of the station positions) and a radius of 20 km, as shown by the black circle in Figure 1. The LMA should have high detection efficiency at this close distance. Only flashes with at least 80% of the sources within the region were temporarily considered.

2.2. Data Processing

The constant altitude plan position indicator reflectivity by the Fukui radar, with 1-km horizontal and vertical resolution, provided by the Japan Meteorological Agency and the Wajima sounding profiles obtained from the University of Wyoming are directly used.

Based on previous studies (e.g., Lund et al., 2009; Zheng & MacGorman, 2016), only LMA sources with chi-square goodness-of-fit values of <2 were chosen. We employed the algorithm introduced by MacGorman et al. (2008) to reconstruct flashes from their sources. In the algorithm, a potential flash source must occur within 150 ms of the previous sources and within 3 km and 500 ms of any other flash source, and the flash duration is limited within 3 s.

A flash is typically initiated between two regions with opposite polarity charges and is therefore closely associated with charge structure. Lund et al. (2009) suggested a method to obtain the initiation location of a flash, which calculates the centroid of the compact cluster for the 10 initial source points. The source points in the compact cluster were required to have a standard deviation smaller than 500 m. If the 10 original points did not satisfy the above condition, then a subset containing any nine points was analyzed, which was repeated until the above condition was met or only five points remained. The average location of the source points associated with the smallest standard deviation in the subset was taken as the flash initiation location. Caicedo et al. (2018) employed the above method to obtain the flash initiation power by calculating the average power of the final chosen sources. In this study, we obtained the flash initiation power in the 66- to 72-MHz frequency range using the same definition and method as those in Caicedo et al. (2018). However, by checking each flash, we found that the initiation locations based on the above method tended to be located within the charge region. One reason was speculated to be that the distances between charge regions in the studied winter storms were small. We then manually determined the initiation location by examining the height changes in the sources during the initial stage of the flash. In most of the investigated flashes (87/119), the first located source was identified to obtain the initiation location, while for other flashes, the leading one or several sources (universally smaller than three sources, occasionally between 3 and 10 sources) were neglected because they were chaotic in terms of height change and the following primary source that preceded the successive source height change was analyzed to obtain the initiation location.

The radiation source data can be used to infer the charge regions based on the concept that the flash leader propagates through a charge region with opposite polarity (e.g., Coleman et al., 2003; Rust et al., 2005; Shao & Krehbiel, 1996). Therefore, deciding the breakdown polarity of the sources is a prerequisite for identifying the charge regions. We manually assigned the polarities of the sources involved in a flash by referring to the
different features between positive and negative lightning leaders. First, a negative leader usually features greater VHF radiation power than a positive leader (e.g., Rison et al., 1999; Shao & Krehbiel, 1996; Thomas et al., 2001). Second, a negative leader typically has a mean speed on the order of 10^5 m/s, which is larger than the mean speed of the positive leader, which is typically on the order of 10^4 m/s (van der Velde et al., 2018; Williams & Heckman, 2012).

We explain this based on a lightning flash case occurring at 01:08:03.912 UTC on 2 December 2014, as shown in Figure 2. This case was an upward bipolar lightning flash initiated from a lightning protection tower. Its base current was measured; therefore, the polarities of the leaders were tested by investigating the

**Figure 2.** An example showing the differences in positive- and negative-breakdown leaders in the context of radiation power and speed based on a flash case occurring at 01:08:03.912 UTC on 2 December 2014. (a) Source altitude versus time. (b) and (c) Distances of the sources from their initial locations versus time. (d) Planar view of the sources where the coordinate origin is placed at the initiation position of the flash. (e) West-east vertical view. (f) South-north vertical view. The colors in (a) and (b) indicate the radiation power of the sources, with the values shown in the right-hand color bar. The warm (cold) colors in (c)–(f) indicate the positive (negative) charge region where the negative-breakdown (positive-breakdown) channels propagate, while the sources in gray color indicate that their polarity is not clear or they are hypothesized to not be in the identified charge regions. In (b) and (c), the pink dotted lines indicate a speed of 10^5 m/s, and the gray dotted lines indicate a speed of 10^4 m/s. The speeds refer to the change in distance of the sources relative to the flash initiation position. The polygon shown by the black solid line in (d) shows the convex hull encompassing all sources. The black dashed line in (d) connects the two sources with the maximum distance and indicates the flash distance.
synchronous recordings of the current and LMA sources. Shi et al. (2018) analyzed this flash and the current measurements in their study on the polarity reversal feature of the leader in upward bipolar lightning.

In Figure 2, the negative channels featured stronger power and greater speed than the positive channels (by comparing Figures 2a–2c). It should be noted that due to the diversity of lightning and the complexity of channel development, it is difficult to quantify the power and speed thresholds that are applicable for all lightning flashes. Therefore, we manually analyzed each lightning. For some parts of the channels, their polarities could be readily assigned based on their distinct characteristics in power and speed. For the other parts of the channels, which did not clearly show the characteristic features, their polarities were assigned by investigating the associations of their behavior with the already determined channels in time and space, relying on subjective judgment with preexisting knowledge on lightning discharge. Even so, a few flashes with chaotically distributed sources could not be polarity classified with confidence. These flashes are not considered. The numbers of flashes with assigned polarities are shown in Table 1. Ultimately, a total of 119 flashes were chosen from the three thunderstorms, accounting for 87.5% of the total flashes with more than 80% of sources being located within 20 km of the LMA center.

The properties of flashes including duration, horizontal distance, and area of the convex hull are also investigated. The flash spatial size can be a proxy for the extent scale of valid charge regions for lightning propagation, a concept employed in previous studies on electrical summer storms (e.g., Bruning & MacGorman, 2013; Calhoun et al., 2013; Zhang et al., 2017a; Zheng et al., 2018; Zheng & MacGorman, 2016) and winter storms (e.g., López et al., 2017; Schultz et al., 2018; Yoshida et al., 2018). The flash duration indicates the time difference between the last source and the first source. The horizontal flash distance is indicated by the black dashed line in Figure 2d and describes the maximum distance between any two sources in a flash. A convex hull is the 2-D polygon constructed from all sources of a flash and featuring the minimum area that collects all the sources, as shown by the black solid lines in Figure 2d.

2.3. CG Flash Data

The Japanese Lightning Detection Network CG flashes were matched with the LMA flashes with the following criterions: (1) return strokes of CG flash must occur during the progression of the LMA flash (a 0.01-s tolerance was added to the start and end of the LMA flash, considering the possible time difference between two location systems and possible underestimation of LMA on flash duration); (2) in 5-km range of return strokes, at least one LMA source should belong to the matched LMA flash; (3) the maximum absolute current among the return strokes of a CG flash must be larger than 15 kA. As a result, a total of 32 CG flashes were matched with the investigated LMA flashes. Some information of the CG flashes is shown in Table 2.

The high ratio of PCG lightning (100% for 12 November, 81% for 14 November, 38% for 2 December, and 66% for all three cases) and great positive peak current (medians of 39 kA for 12 November, 59 kA for 14 November, 78 kA for 2 December, and 67 kA for all three cases) and relatively frequent bipolar lightning (a total of three bipolar CG flashes) agreed with previous studies on the lightning characteristics in winter thunderstorms (Goto & Narita, 1995; Ishii & Saito, 2009; Narita et al., 1989; Shi et al., 2018; Suzuki, 1992; Takeuti et al., 1976; Wang et al., 2008). Compared with the LMA flashes (Table 1), the thunderstorm on 12 November had the lowest ratio of CG lightning (~6%), followed by 2 December (~32%), and 14 November (~52%).

However, in all the matched LMA flashes, we could not intuitively find clear feature associated with return stroke only from the located sources, such as apparent leader progression toward the ground, which made it difficult to identify the origin charge consumed by the CG flashes, an important issue in the study on...
Japanese winter thunderstorm. For the sake of integrity, in the following we will not do any further analysis
on the CG flash. Instead, we will focus on the charge distributions suggested by LMA flashes.

### 3. Analysis and Results

All three thunderstorms comprised many scattered storm cells when referring to the radar echoes. Here, the
default cell has a continuous region with composite reflectivity above 30 dBZ. Because the analysis is limited
to a small fixed space and the cells usually crossed the analysis area in a short time, it was difficult to inves-
tigate the evolution of charge distributions during the entire lifetime of cells. Therefore, the investigated
flashes possibly came from different cells that might be at different development stages. In addition, the time
resolution of the radar data was 10 min, which might cause the spatial correspondence between flashes and
radar echoes in space to not be very consistent.

#### 3.1. Vertical Charge Distributions in the Thunderstorm on 12 November 2014

The winter thunderstorm on 12 November 2014 moved rapidly from southwest to northeast. The 47 inves-
tigated flashes occurred between 0710 and 0750 UTC in the analysis region. The sequences of flashes and
sources are shown in Figure 3. Most of the flashes indicated the pattern of negative charge above positive
charge, while a few flashes indicated extra positive charge at a high level. In general, the negative charge
was mainly located between the −10 and −20 °C isotherms, while the positive charge below it was mainly

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**Table 2**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>12 November</th>
<th>14 November</th>
<th>2 December</th>
<th>All thunderstorms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number of CG flashes</strong></td>
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<td>16</td>
<td>13</td>
<td>32</td>
</tr>
<tr>
<td><strong>PCG Flashes</strong></td>
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<td>13</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td><strong>Median of peak current (kA)</strong></td>
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<td>59</td>
<td>78</td>
<td>67</td>
</tr>
<tr>
<td><strong>NCG Flashes</strong></td>
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<td>1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td><strong>Median of peak current (kA)</strong></td>
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<td>−18</td>
<td>−34</td>
<td>−29</td>
</tr>
<tr>
<td><strong>Bipolar CG Flashes</strong></td>
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<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Median of peak current (kA)</strong></td>
<td>—</td>
<td>79</td>
<td>123</td>
<td>86</td>
</tr>
</tbody>
</table>

*a* Referred to the maximum peak current among the return strokes involved in a CG flash.

*b* The positive return strokes in the bipolar CG flashes always had the maximum peak current.

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**Figure 3.** Altitudes of sources versus sequence of flash sources during the winter storm on 12 November 2014. The warm and cold colors indicate the positively and negatively charged regions, respectively. The sequence number of the investigated flashes is labeled on the top x axis, and the corresponding start time of the radar volume scan in 10-min interval is labeled on the bottom x axis. The green squares represent the flash initiations. The black solid line and dotted line represent the maximum heights of the 20- and 40-dBZ echo tops, respectively, within 20 km of the LMA center. The isotherms from the sounding at 1200 UTC on 12 November 2014 are labeled by gray dashed lines, with the temperature values marked on the right.
around and below the −10 °C level and that above it was typically above the −20 °C level. The ashes occurred predominantly below 6 km, while most of the ashes were initiated between 3 and 4 km, roughly corresponding to the −10 and −15 °C isotherms.

We further investigated the charge distribution from the perspective of specific cells in the thunderstorm by considering frequent flash stages and the representativeness of the charge distribution. Forty-one of 47 flashes that occurred during 0710–0730 UTC seemed to be caused by the same storm cell. We show the radar reflectivity and flash sources with their breakdown polarities in Figure 4.

According to Figure 4, the storm cell had two main charge regions involved in the lightning discharges, with the main negatively charged regions being above the main positive regions. According to the vertical cross section of reflectivity (Figures 4e1, 4e2, 4f1, and 4f2), large charge densities (suggested by large number of sources) were located near the region with convection, as suggested by the large radar echoes reaching high levels. Near the strong convection during 0710–0720 UTC (Figures 4a1–4f1), the core of the main negatively charged region corresponded to a reflectivity of generally <40 dBZ and was mainly located between −15 and −20 °C levels, while the corresponding value for the core of the main positively charged region was between 40 and 50 dBZ and between −10 and −15 °C levels. The main charge cores decreased in height during 0720–0730 UTC (Figures 4a2–4f2), with their corresponding temperatures being around −15 °C for the main negative charge core and −10 °C for the positive charge core, respectively. This result should be associated with the reduced convection suggested by the decrease in the echo top. In the regions outside of the
convection, the distribution of main negative charge above the main positive charge remained, but the altitudes of the charge regions decreased. In addition, during both periods, a second positively charged region located at the top of the cell was indicated by a total of four flashes (Figures 4a1 and 4a2), with its associated temperature being around and smaller than \(-20^\circ\)C and radar echoes being mainly smaller than 30 dBZ during 0710–0720 UTC and 15 dBZ during 0720–0730 UTC. During 0710–0720 UTC, a small negative charge corresponding to a radar reflectivity generally greater than 50 dBZ was suggested by two flashes (Figure 4a1) under the main positively charged region during 0710–0720 UTC, but disappeared during 0720–0730 UTC.

The remaining six flashes corresponded to the radar volume scan periods from 0730 to 0750 UTC and were mainly concentrated in two separate areas (Figure 5). The flashes occurring between 0730 and 0734 UTC were located in the north of the analysis region, as shown in Figures 5a1–5f1. They proposed a relatively complex charge distribution. Along the direction of the vertical cross section from point A to point B, an upper positively charged region and a lower negatively charged region were suggested at distances from 0 to 10 km and 18 to 40 km, respectively. Between 12 and 18 km, upper negatively charged and lower positively charged regions were indicated. The main positive charge was located around the center of the analysis region during 0710–0720 UTC, but disappeared during 0720–0730 UTC.

In Figures 5a2–5f2, the three flashes occurring near the center of the analysis region indicated a vertically compact charge distribution, including an upper negatively charged region above \(-20^\circ\)C and a lower positively charged region below \(-10^\circ\)C. The most concentrated areas of the two charge regions were between two convection areas, and thus, the positively charged region corresponded to 20–40 dBZ and the negatively charged region around \(-10^\circ\)C.
charged region corresponded to 15–30 dBZ. However, given the low time resolution of the radar and the rapid movement of the cells, it was likely that the main charge regions in fact corresponded to the convection areas.

### 3.2. Vertical Charge Distributions in the Thunderstorm on 14 November 2014

On 14 November 2014, the thunderstorm containing a large number of scattered cells moved from west to east. A total of 31 flashes produced by multiple cells throughout the analysis region during 1610–2040 UTC were investigated. The flash and source sequences versus altitude are shown in Figure 6. The patterns of the charge distributions were diverse, while the discharges mainly occurred between the levels of 0 and –20 °C. We then selected several cells with representative charge patterns yielding relatively frequent flashes for further analysis.

Figure 7 shows two flashes associated with a cell during 1610–1620 UTC. The pattern of the positively charged region above the negatively charged region was indicated by the LMA sources at a distance from 8 to 20 km along the vertical cross-section A–B. The positive charge was mainly located between –5 and –20 °C at levels from 2 to 4 km, which was associated with a reflectivity of <45 dBZ, while the corresponding values for the negative charge were between 0 and –10 °C, from 1 to 2.5 km and >30 dBZ, respectively. In the distance ranging from approximately 0 to 7 km along A–B, a positive charge was indicated to be located around 0 °C (Figure 7e), while a negative charge was faintly proposed by several scattered negatively marked grid boxes at the distance of ~7 km along A–B and around –10 °C.

During 1810–1830 UTC, a cell associated with the lines A–B in Figure 8 yielded seven flashes. In the first 10-min stage, four flashes indicated the charge distribution pattern of the second positive, main negative, main positive, and second negative charges from top to bottom, while the charged regions were tilted in the vertical direction (Figures 8e1–8f1). The main negatively charged region crossed the isotherms from –5 to –15 °C, corresponding to an altitude from ~1.5 to 4 km. The main positively charged region was located between 0 and –10 °C, corresponding to an altitude between ~1 and 2.5 km. A large part of the main negative charge corresponded to a reflectivity between 20 and 40 dBZ, while the positively charged core was mainly located in the region with a reflectivity of >30 dBZ. The second upper positive charge, which was also tilted in the vertical direction, occurred in the region with reflectivity smaller than 20 dBZ, with the height of the core being ~4 km. The second negative charge at the bottom was around 0 °C and mainly associated with a reflectivity of >40 dBZ.

In the second 10-min stage, three flashes were associated with the cell. The pattern of the charge distribution was similar to that in the first 10-min stage, except that the bottom negative charge was not indicated, and the heights of the charged regions were reduced slightly due to the decreasing convection suggested by the radar echo top. The upper second positively charged region mainly corresponded to a reflectivity of <25 dBZ. For the main negatively and positively charged regions, their associated radar echoes were between 25 and 40 dBZ and greater than 30 dBZ, respectively.
Figure 9 shows the flashes during 1910–1920 UTC (Figures 9a1–9f1) and 2030–2040 UTC (Figures 9a2–9f2), respectively. They both indicated the charge pattern of upper negative, middle positive, and lower negative charges.

During 1910–1920 UTC, in the convection location of the cell suggested by the prominent radar echo (~5–15 km at line A–B in Figures 9e1 and 9f1), the middle positive charge was distributed around −10 °C, bias toward the levels between 0 and −10 °C and mainly occupied the areas with a reflectivity between 25 and 40 dBZ, while the upper negative charge was located around −20 °C and associated with a reflectivity of <25 dBZ and the lower negative charge was mainly located between 0 and −5 °C and associated with radar echo between 30 and 45 dBZ. According to the source density and flash initiations, the two negatively charged regions, together with the positive region, all contributed to the flash initiation and discharge; therefore, these regions might be regarded as the main charge regions together.

At the location between 15 and 25 km along the line A–B (Figures 9e1 and 9f1), the charge regions included an upper positive charge mainly between −10 and −20 °C and a small negative charge of approximately −10 °C, while their associated radar echoes were smaller than 20 dBZ and around 25 dBZ, respectively.
As shown in Figures 9a–9f, the flashes during 2030–2040 UTC indicated two main charge regions: the upper negative between −10 and −20 °C (between 3 and 4 km) and the middle positive mainly between 0 and −10 °C (between 1 and 3 km); meanwhile, a second negatively charged region was below the middle positively charged region and around 0 °C. The upper negatively charged region corresponded to a reflectivity of <25 dBZ, and the main part of the middle positively was associated with a reflectivity between 25 and 35 dBZ. The lower negatively charged region featured a larger reflectivity.

3.3. Vertical Charge Distributions in the Thunderstorm on 2 December 2014

The thunderstorm on 2 December 2014 moved from west to east. A total of 41 flashes were investigated in the analysis region, and their source sequences with altitude are shown in Figure 10. Except for the first flash that occurred between 0100 and 0110 UTC (shown in Figure 2), the other flashes occurred from 1430 to 2130 UTC. Figure 10 shows that most of the flashes indicated the upper positively and lower negatively charged regions, while the former was mainly located around −20 °C, generally crossing the levels from −10 to −30 °C, and the latter was mainly located around −10 °C level, generally crossing the levels from 0 to −20 °C. There were three flashes (including the flash shown in Figure 2) that were initiated at very low heights (0.25, 0.38, and 0.28 km indicated by the LMA sources, respectively; see Figure 10); they were speculated to be upward lightning flashes initiated from ground objects according to the source data. The charge distribution was also further investigated by choosing cells with relatively frequent flashes and representative charge distributions.

Figure 11 shows flashes during two consecutive periods from 1820 to 1830 UTC and 1830 to 1840 UTC. The flashes indicated the positively charged region above the negatively charge regions. The positive charge was...
mainly distributed between −20 and −30 °C levels and corresponded to a reflectivity around and smaller than 30 dBZ. The negative charge was mainly located between −5 and −20 °C levels and associated with a reflectivity of >30 dBZ.

The flash in the south cell in the analysis region during 1830–1840 UTC indicated another type of charge distribution (Figure 12). The positively charged region was located mainly between −10 and −20 °C levels, while

Figure 9. Lightning Mapping Array flashes and indicated charge regions during 1910–1920 UTC (a1–f1) and 2030–2040 UTC (a2–f2) on 14 November 2014. The explanation is the same as that in Figure 4.

Figure 10. Same as Figure 3 but for flashes during the winter thunderstorm on 2 December 2014. The isotherms were derived from the sounding at 0000 UTC on 3 December 2014.
the negatively charged region was below −10 °C level. They typically featured the radar echoes of <35 and >30 dBZ, respectively. The charge pattern indicated by the 31st flash occurring between 1940 and 1950 UTC in Figures 13a1–13f1 had a negatively charged region above and a positively charged region below the −10 °C level. The radar echoes of these two charged regions were predominately 20–30 dBZ and greater than 30 dBZ, respectively. Figures 13a2–13f2 show that the 32nd flash had a higher negatively charged region around −20 °C level (corresponding to a ~10–dBZ echo) and a positively charged region mainly below −10 °C level (corresponding to a reflectivity of 20–30 dBZ).

The 39th and 41st flashes indicated another type of charge distribution. As the 40th flash occurred spatially close to these flashes (Figure 14), they were investigated together. In the right convection cell, the charge pattern indicated by the 40th flash was positive above negative. The positively charged region was located around the −20 °C level with a reflectivity between 10 and 35 dBZ, and the negatively charged region was located around the −10 °C level with a reflectivity of >35 dBZ. At distances of 2–25 km along the line A–B, the positively charged region was located mainly between −10- and −20 °C levels and was superimposed on a reflectivity between approximately 10 and 35 dBZ, the same as that in the right convection region. However, the negatively charged region involved in the lightning discharge was at a higher level, around −20 °C between 4 and 6 km, where the radar echoes were smaller than 10 dBZ. We speculate that the negative charge should be located in the top screening layer.

3.4. Vertical Distributions of Charged Cores

In this section, the number of positive- and negative-polarity sources in each flash was counted in 0.2-km height bins. The heights with peak source numbers were defined as the heights of the charged cores. The channels of some flashes changed substantially in the vertical direction, which made it difficult to clearly determine the height of the charged core; these flashes were removed. Finally, the charged cores inferred...
from a total of 101 flashes were obtained, including 43 samples on 12 November, 18 samples on 14 November, and 40 samples on 2 December.

Figure 15 shows the distribution of the charged cores with height. On 12 November 2014 (Figure 15a), the negatively charged cores ranged from 1.7 to 4.5 km, but most of them (38/43) were located between 3.1 and 4.5 km. The positive cores ranged from 1.3 to 3.9 km, but most of them (40/43) were located between 2.3 and 3.5 km. When counted in 0.4-km height bins (associated with the polylines and bars in Figure 15), the peak height of the negatively charged core spanned from 3.4 to 4.2 km, and that of the positively charged core was located at 3 km. The negatively charged cores on 14 November 2014 (Figure 15b) changed from 1.1 to 4.9 km. For the positively charged cores, the corresponding range was from 1.9 to 4.3 km, but most of them (15/18) were between 1.9 and 3.3 km. The negatively and positively charged cores hit the peak at 2.2–2.6 km and 2.2 km, respectively. According to Figure 15c, the cells on 2 December 2014 contributed to the large height range for the negatively charged cores, with values between 0.7 and 5.3 km, but most of the negatively charged cores (38/40) occurred from 0.7 to 3.3 km. The positively charged cores varied from 1.5 to 4.5 km and

Figure 12. Lightning Mapping Array flashes and indicated charge regions during 1830–1840 UTC on 2 December 2014. The explanation is the same as that in Figure 4.
were concentrated between 2.5 and 4.5 km (35/40). The peak heights of the negatively and positively charged cores were 2.6 and 3.8 km, respectively.

By combining the samples of the three thunderstorms (Figure 15d), the negatively and positively charged cores were distributed between heights of 0.7 and 5.3 km and 1.1 and 4.5 km, respectively. Both the peaks of the positively and negatively charged cores were between 3 and 3.4 km, while the positively charged cores were more concentrated between 2.2 and 3.8 km, but the negatively charged cores were widely distributed between 1 and 4.6 km.

Figure 16 shows the distribution of the charged cores with temperature. In the investigated cells on 12 November 2014 (Figure 16a), the negatively charged cores approximately corresponded to the isotherms from −1 to −19 °C, with values primarily ranging from −10 to −19 °C (40/43). The positively charged cores approximately ranged from 2 to −15 °C, while 40 of the 43 samples were distributed between −6 and −12 °C. Most of the positive and negative charges were separated by approximately −12 °C. When counted in 3 °C bins, the peaks of the negatively and positively charged cores were both −11 °C, but many of the negatively charged cores clearly occurred at levels with isotherms less than −11 °C. The charged cores in the cells on 14 November 2014 (Figure 16b) approximately ranged from −1 to −24 °C for the negative charge and from −7 to −21 °C for the positive charge, showing scattered distributions with the isotherms. On 2 December 2014 (Figure 16c), the negatively and positively charged cores approximately corresponded to the isotherms from −1 to −31 °C and from −7 to −26 °C, respectively. Most of the negatively and positively charged cores were separated by approximate −15 °C isotherms, with their peaks ranging from −11 to −14 °C and being at −23 °C, respectively.
When all cells were considered together (Figure 16d), the negatively charged cores ranged from –1 to –31 °C, hitting a peak from –10 to –16 °C. The corresponding values of the positively charged cores ranged from 2 to –26 °C and –7 to –10 °C. Meanwhile, the positively charged core had a second peak from –22 to –25 °C.

Statistics on the distances between the adjacent opposite-polarity charge cores are shown in Figure 17 and Table 3. Approximate 81% (82/101) flashes had the distances between 0.5 and 2 km, with the peak interval being between 1 and 1.5 km (Figure 17a). According to the mean (median) distances (Table 3), the storm cells on 2 December had the maximum mean (median) value of 1.6 km (1.6 km), followed by those on 14 November with value of 1.4 km (1.3 km), and those on 12 November with value of 1.0 km (1.0 km). Considering the three winter thunderstorms together, the distances between the adjacent charge cores ranged from 0.2 to 3.4 km, with the mean of 1.3 km and median of 1.2 km (Figure 17b and Table 3).

3.5. Flash Size and Its Suggested Horizontal Extent of the Charge Region

All 119 flashes were counted to obtain the flash duration, horizontal distance, and convex hull area distributions, as shown in Figure 18. When all flashes were considered, most samples were concentrated between
200 and 300 ms for flash duration, 15 and 25 km for the horizontal distance of flash, and below 200 km$^2$ for the area of the convex hull of the flash. The flashes lasted from 47.2 to 3130.7 ms, with a mean of 425.0 ms and a median of 297.7 ms. The horizontal distance of the flashes changed between 4.8 and 45.4 km, yielding a mean of 19.8 km and a median of 18.3 km. The area of the convex hull of the flash ranged from 9.5 to 789.7 km$^2$, with a mean and median of 176.2 and 142.6 km$^2$, respectively.

The spatial size of the flash can be a proxy for the extent of the charge region that can support the propagation of flash channels (we temporarily refer to this as the valid charge region). For example, the horizontal distance of the flash should reflect the horizontal extent length of the valid charge region, which we deduced to be ~20 km on average according to the mean flash distance. If the average area of the convex hull of the flash was approximated to the area of the valid charge region (e.g., Zheng et al., 2018), the mean equivalent diameter of the valid charge regions was estimated to be ~15 km when the valid charge region was assumed to be in a circular shape.

### 3.6. Flash Initiation Position and Power

In the statistical results of the flash initiation, the three flashes identified as upward flashes initiated from ground objects on 2 December 2014 were excluded. The distributions of the remaining 116 flashes with height and temperature are shown in Figure 19. The investigated flashes were initiated between 0.8 and 4.1 km, with the median and mean both being approximately 2.8 km. Approximately 78% (91/116) of the flashes were concentrated within an initiation height of 2 and 3.5 km, with the peak interval being 3−3.5 km. The ambient atmospheric temperature at the flash initiation location ranged from approximately 1.6
to $-24.9 \, ^\circ C$, with a mean of $-11.9 \, ^\circ C$ and a median of $-10.7 \, ^\circ C$. There was an outstanding temperature interval between $-12$ and $-8 \, ^\circ C$, which acquired the most flashes initiations.

The distribution and statistics of the flash initiation power are shown in Figure 20 and Table 4. According to Figure 20a, most of the flashes in the three winter thunderstorms had the initiation powers between 10 and 20 dBW. By comparing their distribution in box-and-whisker plot (Figure 17b) and the statistical values in Table 4, the flashes on 2 December were of the largest initiation power according to their means or medians and their 25th and 75th percentiles, sequentially followed by those on 14 and 12 November, with their medians (means) were 19.2 (18.5), 16.3 (17.1), and 12.4 dBW (12.3 dBW), respectively. The 116 flashes had the initiation power from $-5.6$ to $31.4$ dBW, yielding the mean and median values of both 15.6 dBW.

4. Summary and Discussions

4.1. Charge Structure

According to the analysis in sections 3.1–3.3, it is found that the distribution patterns of the charge regions involved in the discharges were diverse. By predominantly referring to the charge distributions in the vertical cross sections in sections 3.1–3.3 (they represented the main patterns of the charge distribution in this study), we give a concept sketch showing the positive and negative charges and their associated ambient atmospheric temperature in Figure 21 where we retain the main shapes and positions of charge regions and ignore the minor details of the edge shapes and the tiny scattered charges.

The LMA sources can only indicate the charge regions taking part in lightning discharges, which is more different from the observations of sounding through the storm (e.g., Takahashi et al., 1999, 2017, 2018).
that may provide evidence for charge region not involved during the discharges of their paths. If only referring to the vertical arrangements of the charge regions included in discharges, the charge structures contained quad-polar structures (Figures 21a1 and 21b2; the charges from top to bottom were positive, negative, positive, and negative), triplolar structures (Figures 21a2 and 21b3; upper positive, middle negative, and lower positive), dipolar structures (Figures 21b1 (the main part), 21c1, 21c2, and 21c3; upper positive and lower negative), inverted dipolar structures (Figures 21a4, 21c4, and 21c5; upper negative and lower positive) and inverted triplolar structures (Figures 21a3, 21b4, 21b5, and 21c6; upper negative, middle positive, and lower negative). In contrast, in most previous studies, winter thunderstorms were suggested to have dipolar or triplolar charge structures (Brook et al., 1982; Caicedo et al., 2018; Kumjian & Deierling, 2015; Schultz et al., 2018; Takahashi et al., 1999, 2017, 2018), which was similar to normal summer thunderstorms (Williams, 1989). As we mentioned in the beginning of section 3, due to the limit of the observation range of the LMA and the rapid movement of thunderstorms, the cells producing the investigated flashes might be in different development stages; therefore, the diverse patterns of the charge distributions, as shown in sections 3.1–3.3 and summarized in Figure 21, might have resulted from both the differences in diverse cells and distinct evolution stages.

On the other hand, we consider the association of charge regions with the ambient temperature and particles. Takahashi et al. (1999, 2017) indicated that riming electrification was a major charge separation mechanism, as suggested by laboratory experiments of Takahashi (1978). They reported that the average reversal temperature of the charge sign was −11 °C. That is, with a moderate cloud water content, graupel

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>12 November</th>
<th>14 November</th>
<th>2 December</th>
<th>All thunderstorms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum (km)</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Maximum (km)</td>
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<td>2.8</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Mean (km)</td>
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<td>1.4</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Median (km)</td>
<td>1.0</td>
<td>1.3</td>
<td>1.6</td>
<td>1.2</td>
</tr>
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</table>
gained positive charge at levels with temperatures higher than the reversal temperature and negative charge at levels with temperatures lower than the reversal temperature, while ice crystals colliding with graupel gained charge with polarity opposite that of graupel. The positively charged small-size ice crystals were transported by vertical airflow toward upper levels, forming the upper positively charged region; the negatively charged graupel and ice crystals concentrated at midlevels formed the middle negatively charged region, and the lower positively charged graupel created the lower positively charged region (Takahashi et al., 1999, 2017, 2018). Based on the videosonde observations, Takahashi et al. (1999) suggested that in the tripolar structure of winter thunderstorms in the Hokuriku region of Japan, the lower positive charge was mainly located below −10 °C, the middle level strongly negative charge mainly occurred between −10 and −20 °C, and the upper positive charge was above −25 °C. Although the atmospheric isotherms coming from the soundings in this study were slightly different from the temperatures measured in the cloud, a large number of previous studies on charge structure associated with ambient atmospheric temperature have suggested that essential associations between the two are consistent with the suggestion of the electrification mechanism.

Figure 18. Distributions of flash duration (a1 and a2), horizontal distance (b1 and b2), and area of the convex hull (c1 and c2). The explanation of the box-and-whisker plots (a2, b2, and c2) is the same as that in Figure 17.
Two of the positive dipole structures in Figures 21c1 and 21c2 were attributed to riming electrification. The main negatively charged regions were located between the −10- and −20 °C isotherms and were characterized by a relatively strong reflectivity (>30 dBZ). They therefore seemed to be associated with the graupel gaining negative charge. The upper positively charged regions, located mainly above the −20 °C isotherm and corresponding to a small reflectivity, appeared to be associated with ice particles or their aggregations. Similar conclusions could be drawn for the positive dipole structure at the right side of Figure 21c6.

**Figure 19.** Distributions of the initiation height (a1 and a2) and ambient atmospheric temperature (b1 and b2). The explanation of the box-and-whisker plots (a2 and b2) is the same as that in Figure 17.

Two of the positive dipole structures in Figures 21c1 and 21c2 were attributed to riming electrification. The main negatively charged regions were located between the −10- and −20 °C isotherms and were characterized by a relatively strong reflectivity (>30 dBZ). They therefore seemed to be associated with the graupel gaining negative charge. The upper positively charged regions, located mainly above the −20 °C isotherm and corresponding to a small reflectivity, appeared to be associated with ice particles or their aggregations. Similar conclusions could be drawn for the positive dipole structure at the right side of Figure 21c6.

**Figure 20.** Distributions of flash initiation power. (a) Distributions of number and cumulative probability. (b) Distribution in box-and-whisker plot.
The quad-polar structures in Figures 21a1 and 21b2, the tripolar structures in Figure 21a2, and the inverted dipolar structure in Figure 21a4 each had the main negatively charged regions above the main positively charged regions, with the two regions approximately separated by the \(-10^\circ C\) isotherm. Meanwhile, the main positively charged cores were located in areas featuring radar echoes of >30 dBZ, which suggested that the lower main positively charged regions were primarily associated with positively charged graupel. Their main negative charge cores corresponded to reflectivity of approximately around and smaller than 30 dBZ, suggesting the contribution of negatively charged ice crystals or their aggregations. The upper second positively charged regions in Figures 21a1, 21a2, and 21b2 were mainly located near or above \(-20^\circ C\) and around and smaller than 20 dBZ; therefore, they should be associated with positively charged ice crystals. The distribution of charge regions in Figure 21b3 was the same as that in Figure 21b2 but with lower heights and dissipated small negatively charged regions at the bottom, which should be due to weakened convection of the cell (proposed by the decrease of the echo top from Figures 21b2 to 21b3) causing the descent of charged particles. The second bottom negative charge regions in Figures 21a1 and 21b2 that were located at \(-0^\circ C\) and corresponded to a strong reflectivity of >40 dBZ might be associated with falling negative graupel. In general, the charge region distribution with temperature was analogous to that suggested by Takahashi et al. (1999, 2017, 2018).

![Figure 21](image)

**Figure 21.** Conceptual charge distributions superimposed on radar echoes according to the analysis of the LMA flashes in sections 3.1–3.3. The time labels correspond to those in sections 3.1–3.3. In addition, “0730–0750 UTC a” corresponds to Figures 5a1–5f1; “0730–0750 UTC b” corresponds to Figures 5a2–5f2; “1830–1840 UTC a” corresponds to Figures 11a2–11f2; and “1830–1840 UTC b” corresponds to Figure 12.
Although all the aforementioned charge distributions appeared to be associated with the riming electrification mechanism (Takahashi, 1978; Takahashi et al. (1999, 2017, 2018), their main positively charged regions could be located either at the upper level (Figures 21c1, 21c2, and the right part of Figure 21c6) or at the lower level (Figures 21a1, 21a2, 21a4, 21b2, and 21b3). Therefore, active electrification in the former situation should occur in regions cooler than the reversal temperature, while in the latter situation predominant electrification likely occurred in regions near or warmer than the reversal temperature. Patterns similar to that with an outstanding lower positively charged region have also been reported for some winter thunderstorms. For example, Takahashi et al. (1999) reported that predominantly negatively charged graupel and ice crystals contributed to the upper negatively charged region, and the positively charged graupel contributed to the main lower positively charged region in three January 1993 winter storms in the Hokuriku area, when there was a uniform downdraft of 2 m/s throughout the clouds. Caicedo et al. (2018) reported that during the first hour of the analysis period for the 2 April 2016 storm in north central Florida, the lower positively charged region in the tripolar structure had approximately twice the amount of LMA sources as the upper positively charged region, indicating larger amounts of charge in the lower positively charged region. We speculate that the strength of convection might be an important influence factor. Under weak convection, ice-phase particles cannot be transported to high levels and, therefore, concentrate at lower levels, forming the main electrification region around the −10 °C level. In contrast, strong convection can transport and concentrate ice particles in areas cooler than the reversal temperature, forming the main charged regions at the upper- and lower-temperature levels. Similar viewpoint was also suggested by Takahashi et al. (1999).

Evidence for this is that the vertical development of the cells in Figures 21c1 and 21c2 were apparently stronger than those in Figures 21a1, 21a2, 21a4, 21b2, and 21b3, with the 40-dBZ echo top in the former being above the −20 °C level, whereas that in the latter being below the −20- or even the −10 °C level.

The height of charge can be affected by the evolution of convection in a thunderstorm. Takahashi et al. (1999, 2018) and Kitagawa and Michimoto (1994) reported descending charge regions during the decay stage owing to weakened convection. The disappearance of the lower positive charge regions from Figures 21a1 to 21a2 and Figures 21b2 to 21b3 and a significant area reduction of the main lower positive charge region from Figures 21b2 to 21b3 were accompanied by the decreases in radar echo heights, indicating the impact of convection on the charge distribution. The dipolar charge distributions in Figure 21b1 (main part) and 21c3 might be also associated with the weakened convection. Their negatively charged regions were located mainly below the −10 °C level and were associated with a reflectivity greater than 30 dBZ. Meanwhile, their positively charged regions featured ambient temperature mainly lower than −10 °C and a smaller reflectivity. Therefore, the negatively charged graupel and positively charged ice crystals or aggregations were expected to be mainly responsible for their charge patterns. However, the temperature ranges associated with the charging areas were not typical for riming electrification mechanism. Furthermore, their associated radar echoes indicated weaker vertical development than those in Figures 21c1 and 21c2, which shows positive dipole charge structures due to riming electrification.

The descending charge might be also responsible for the charge distribution in Figure 21a3. Figures 21a1–21a3 exhibit the continuous evolution of same thunderstorm over time. From Figures 21a2 to 21a3, the change of radar echo indicated a sharp weakening of thunderstorm convection. In Figure 21a3, the respective correspondence of the main positive and lower negative charge regions to radar echoes of <20 and 15–30 dBZ was same to that of the upper positive and middle negative charge regions in Figure 21a2, which suggested that these two charge regions in Figure 21a3 originated from the upper positive charge and middle negative charge in Figure 21a2. The weakened convection caused the charge regions in Figure 21a2 to drop and made the lower positive charge region disperse in Figure 21a3. The upper local negative charge in Figure 21a3 was speculated to be the residual of the original middle negatively charged region in Figure 21a2.

The inverted charge structures in Figures 21b5, 21c4, and 21c5 might be associated with a snow dipole which featured negative over positive charge and typically occur in stratiform regions or the late stages of storms (Boccippio, 1996; Williams, 2018). According to Williams (2018), collisions between ice crystals and snow/aggregates (fragmentation might also have been involved) may lead to positive charge transfer to the latter just above the 0 °C isotherm and negative charge to smaller crystals at a higher level. In Figures 21b5, 21c4, and 21c5 and the corresponding Figures 9a2–9f2 and 13, the relevant cells featured smaller radar echoes than most of the other investigated cells. Therefore, they might be in the late stages or in the stratiform stage of the thunderstorms. The areas associated with the main positive charges above approximately
the 0°C level had radar echoes predominantly around 20–30 dBZ, suggesting the existence of snow/aggregates. The upper main negative charge located approximately between −10 and −20 °C or around −20 °C corresponded to a reflectivity close to and smaller than 20 dBZ, suggesting negatively charged ice crystals. The charge distribution in the far left of Figure 21b1 might also be associated with a snow dipole, considering that it was located in an area separated from the main body of the cell and characterized by a smaller radar echo (Figure 21b1 or Figure 7) and that the positively charged region was mainly between 0 and −5 °C and associated with a reflectivity around 30 dBZ. However, it should be noted that electrification between ice crystal and snow has not been tested by laboratory experiment or in situ observation, although a few evidences seeming to support it were reported in some summer and transition season storms (Marshall et al., 2009; Shepherd et al., 1996; Williams, 2018). On the other hand, we did not find obvious bright-echo band associated with the melting snow around 0°C level in the relevant radar images. But it might result from the low 0°C isotherm (below 1 km on 14 November and 2 December when the snow dipole was suggested), while the radar constant altitude plan position indicator data provided to us started from 1-km altitude. Furthermore, Williams (2018) also mentioned that “In many winter storms the melting layer is either non-existent or is too close to the earth’s surface to be detected by radar. But the lack of radar ‘bright band’ does not negate the possible existence of the snow dipole.”

The charge pattern in Figure 21b4 is attributed to the weakened convection together with the possible charging between ice crystals and snow/aggregates. On the one hand, the lower negatively charged region corresponded to a reflectivity larger than 30 and even 40 dBZ, suggesting an association with negatively charged graupel. Considering that this region was located between 0 and −10 °C and that the 40-dBZ radar echo was significantly lower than those in Figures 21c1 and 21c2, we speculate that it originated from the descent of the negatively charged graupel from the region above the reversal temperature level. By the way, similar speculation was applied for the bottom second negatively charged region in Figure 21b5. On the other hand, the composite reflectivity in Figure 9e1, which shows relatively weak echoes over a large area, indicates a stratiform or late-stage storm. The main positive charge ranged between the 0 and −20 °C isotherms and corresponded to radar echoes between approximately 15 and 40 dBZ, likely indicating the coexistence of ice crystals, snow/aggregates. The upper negative charge was distributed around −20 °C and was associated mainly with ice crystals, as indicated by a reflectivity of <20 dBZ. Therefore, the charging process between ice crystals and snow/aggregates might be responsible for the upper negative charge and part of the positive charge below it.

The screening layer charge at cloud top might be involved in a few of lightning discharges, as shown in the left and center of Figure 21c6. The dipolar charge structure in the right of the figure was, as mentioned above, likely associated with riming electrification. The radar echoes and spatial continuity suggested that the main positively charged region was associated with the upper ice crystals. The negative charge regions in the left and center of Figure 21c6 were located above the −25 °C level where no reflectivity greater than 10 dBZ was found. Therefore, it was inferred that the negative screening layer participated in the lightning discharges.

The above discussion indicates that convection plays a crucial role in shaping the diversity of the charge patterns in Hokuriku’s winter thunderstorms. With relatively strong convection, the main charge regions tend to be vertically aligned in a positive dipole, such as those shown in Figures 21c1 and 21c2, following the typical charge structure (Brook et al., 1982; Krehbiel, 1986; Takahashi et al., 1999, 2017, 2018; Yoshida et al., 2009). Relatively weak convection tends to cause the main charging between graupel and ice crystals or their aggregations to occur at a warmer level, thus forming a predominately lower positive charge region and a middle negative charge region (i.e., an inverted dipole, as in Figures 21a1, 21a2, 21a4, and 21b2). With reduced convection, the falling of charged particles causes the lower charge region to shrink (Figures 21b2 and 21b3) or disperse (compare Figures 21a1 and 21a2, Figures 21a2 and 21a3, and Figures 21b2 and 21b3), which causes different patterns of charge distribution. Meanwhile, in the stratiform or late-stage storm characterized by the weak convection, the snow/aggregates and ice crystals might be the predominant hydrometeor types in the cloud, and the charging process between them might influence or determine the charge structure, such as in Figures 21b4, 21b5, 21c4, and 21c5. In summary, the convection was associated with the charge pattern of Hokuriku’s winter thunderstorms in two main ways: it affects the charging mechanisms and their locations, and it can alter the height of the charge regions (or even make them disappear). These various factors help to explain the diversity of charge structures.
The charged cores in the studied thunderstorms were distributed between heights of 0.7 and 5.3 km. The heights of the charge regions in winter thunderstorms are understandably lower than those in summer thunderstorms because of the low-altitude isotherms in winter. The same patterns regarding the comparison of charge region heights in winter and summer have been reported in previous studies (e.g., Brook et al., 1982; Caicedo et al., 2018; Yoshida et al., 2018). On the other hand, the charged cores corresponded to isotherms ranging from 2 to –31 °C, which is consistent with those in summer thunderstorms in previous reports (e.g., Krehbiel, 1986; Yoshida et al., 2018). However, nearly all the charge regions occurred in altitude below the –30 °C level in this study (referring to the analysis in sections 3.1–3.3 and Figure 21), which was different from some strong summer thunderstorms, in which many flash source could occur even above the –40-°C level (e.g., Zhang et al., 2017a; Zheng et al., 2009, 2010, 2018; Zheng & MacGorman, 2016). In the comparison of sources in summer and winter, Yoshida et al. (2018) also noted that the ratios of sources at temperatures colder than –10 °C to the total sources in winter thunderstorms were substantially lower than those in summer thunderstorms.

4.2. Horizontal Extent of the Charge Region

The spatial flash size is controlled by the scale of the charge region and can, therefore, be regarded as a proxy for the extent of the charge region. In section 3.5, we obtained the mean (median) values of the flash distance and area of the convex hull to be 19.8 (18.3) km and 176.2 (142.6) km², respectively, and estimated the equivalent diameter of the valid charge region to be ~15 km. In contrast, Schultz et al. (2018) counted the areas of the convex hulls of 34 LMA flashes in four thunderstorms with snowfall in northern Alabama, central Oklahoma, and Washington DC and obtained a median of 128 km². López et al. (2017) explored the mean and median flash lengths (i.e., the major axis of the ellipse fitted to the LMA source points) to be 18.4 and 15.6 km, respectively, in winter over the Ebro Delta (northeastern Iberian Peninsula). Yoshida et al. (2018) documented that the square root of the area of the convex hull for winter flashes around the Japanese Shonai area was 14.8 km, indicating the median area of the convex hull to be ~219 km². Our results on the flash spatial size were within their numerical ranges.

The flash size in winter thunderstorms seemed to be larger than in summer thunderstorms. In the studies mentioned above, López et al. (2017) obtained mean and median flash lengths in summer thunderstorms of 15.0 and 10.3 km, respectively. Yoshida et al. (2018) suggested that the median area of the convex hull of summer flashes around the Japanese Kanto region was approximately 26 km² (counted based on the given square root value). In a New Mexico supercell, Zhang et al. (2017b) showed the mean (median) horizontal distance and area of the convex hull of LMA flashes to be 7.1 (6.1) km and 20.3 (8.2) km², respectively. The corresponding values in an Oklahoma supercell cluster investigated by Zheng et al. (2018) were 7.52 (5.54) km and 36.16 (9.67) km². Therefore, the spatially continuous valid charge region for the propagation of flashes in winter thunderstorms should be larger than that in summer thunderstorms.

4.3. Flash Initiation

Due to the lower height of the charge regions, the height of the flash initiation was certainly lower in winter than in summer. In this study, the mean and median flash initiation heights were both 2.8 km, with a peak interval of 3–3.5 km. As a comparison, Wu et al. (2015) reported the mean initiation heights of negative CG lightning flashes and intracloud lightning flashes to be 5.7 and 7.8 km, respectively, on eight summer thunderstorm days in the Osaka area of Japan.

For the flash initiation power, we obtained the mean and median values to be both 15.6 DBW, with the peaks of the histogram in Figure 20 being between 14 and 16 DBW. In contrast, in the study on the three winter/spring thunderstorms in north central Florida, Caicedo et al. (2018) documented that the peaks of the flash initiation power histogram were approximately 11, 15, and 16 dBW, with their mean value tending to be between 10 and 17 dBW (also in the 66–72 MHz frequency range, similar to this study). Meanwhile, in two other summer thunderstorms, Caicedo et al. (2018) found that the peaks of the flash initiation power histogram were close to 8 and –3 dBW, with the mean initiation power of the investigated summer flashes tending to be between –2 and 6 DBW. Therefore, our results on the flash initiation power were close to those reported by Caicedo et al. (2018) in winter/spring thunderstorms and distinctly larger than those reported by Caicedo et al. (2018) in summer thunderstorms.
We speculate that the larger flash initiation power in winter than in summer is associated with seasonal differences in the charge structures of the thunderstorms. The ambient electric field is typically a crucial determinant of the properties of the initial leader of a flash (Wu et al., 2015; Zheng et al., 2018). Considering that the initiation power was enumerated using the first 10 sources of a flash, the radiation power should be mainly positively related to the ambient electric field supporting the propagation of the initial leader of a flash. Because the electric field required for flash initiation increases as the air pressure increases, the ambient electric field in the cloud is thought to be generally greater at lower altitudes than at higher altitudes. Therefore, the lower initiation height of a flash in winter than in summer meant that winter flashes tend to be initiated and propagated in a stronger electric field, giving them a greater initiation power. As indirect evidence of this speculation, Wu et al. (2015) found that the pulses associated with the initial breakdown of flashes occurred with greater frequency, amplitude, and width at lower altitudes. Furthermore, the larger valid charge area (indicated by the large spatial size of the flash) and the closer distance between adjacent charged regions may also contribute to the formation of a strong electric field in winter thunderstorms, and thus to a stronger initiation power.

5. Conclusions

Using 3-D LMA flash source data, Fukui radar echo data, and Wajima sounding data, the distribution of charge regions involved in the lightning discharges of three thunderstorms in the Hokuriku region of Japan in the winter of 2014 is investigated. The main conclusions are as follows.

The vertical arrangements of the charge regions involved in the LMA lightning discharges suggest diverse types of charge distribution, including quad-polar, tripole, positive dipole, inverted dipole, and inverted tripole. Rimming electrification between graupel and ice crystals (Takahashi, 1978) were thought to be the main mechanism responsible for most of investigated cells. The charging between snow/aggregates (which gain positive charge) and ice crystals (which gain negative charge; Williams, 2018) was supposed to be another mechanism for the inverted charge structure (positively charged region above approximately 0 °C and negatively charged region above it) accompanied with weak radar echoes. Meanwhile, the convection crucially affects the diversity of the charge structure by determining the charging mechanisms and where they mainly occur and by altering the heights of the charge regions (or even making them disappear). Furthermore, a few of lightning discharges appear to occur between the upper positive charge and the overlying negative screening layer.

Some cells exhibit main positively charged regions below the middle main negatively charged region and at a lower level that is warmer than ~ −10 °C. Comparison with cells featuring a typical upper main positively charged region indicates that the cells with lower main positively charged region feature weaker convection indicated by low radar echoes, and therefore the main charging process occurs at around or below −10 °C level, a region where graupel gains positive charge by riming electrification (Takahashi, 1978).

The negatively and positively charged cores in all investigated cells are distributed between heights of 0.7 and 5.3 km and 1.1 and 4.5 km, respectively. Their corresponding temperature ranges are analogous to those in summer thunderstorms, with negatively charged cores ranging from −1 to −31 °C and peaking from −10 to −16 °C and positively charged cores ranging from 2 to −26 °C and peaking from 7 to 10 °C. The positively charged core has a second peak between −22 and −25 °C. The distance between adjacent charged cores ranges from 0.2 to 3.4 km, yielding mean and median distances of 1.3 and 1.2 km, respectively. Approximately 81% of flashes suggest a distance between 0.5 and 2 km, with the peak of the histogram located at 1–1.5 km.

The duration, horizontal distance, and area of the convex hull of the investigated flashes have mean (median) values of 425.0 (297.7) ms, 19.8 (18.3) km, and 176.2 (142.6) km², respectively. We estimate the equivalent diameter of the valid charge region for lightning propagation to be approximately 15 km on average if the charge region is circular and has the same area as the mean area of the convex hull of the flash.

The investigated flashes are initiated between 0.8 and 4.1 km, yielding median and mean values of ~2.8 km and hitting a peak sample number between 3 and 3.5 km. The corresponding values for the ambient atmospheric temperatures associated with the flash initiations are between 1.6 and −24.9 °C, −11.9 °C (mean), −10.7 °C (median), and between −12 and −8 °C. The flash initiation power ranges from −5.6 to 31.4
Acknowledgments
This work was supported by the National Key Research and Development Program of China (2017YFC1501503), the National Natural Science Foundation of China (41675005 and 91537209) and Basic Research Fund of Chinese Academy of Meteorological Sciences (2016Z002). The authors are particularly grateful to R. J. Thomas, H. E. Edens, and P. R. Krehbiel who are working for New Mexico Tech and helped to set up the equipment and provide the data. The data associated with this paper can be accessed from https://doi.org/10.5281/zenodo.2669722 or from the corresponding author.

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Journal of Geophysical Research: Atmospheres


