Evolution of the Charge Structure and Lightning Discharge Characteristics of a Qinghai-Tibet Plateau Thunderstorm Dominated by Negative Cloud-to-Ground Flashes

Yajun Li¹, Guangshu Zhang¹, and Yijun Zhang²

¹Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China, ²Institute of Atmospheric Sciences/Department of Atmospheric and Oceanic Sciences, Fudan University, Shanghai, China

Abstract The correlation between the charge structure evolution and lightning type and frequency for a multicell thunderstorm dominated by negative cloud-to-ground (CG) flash on the Qinghai-Tibet Plateau was analyzed using observations from a three-dimensional lightning very high frequency radiation source location system. The analysis results showed the following. (1) In the initial developing stage of the thunderstorm, each cell developed independently and presented an inverted dipole charge structure. As the thunderstorm developed into its mature stage, multiple cells merged, and the charge structure changed to a tripole structure. In the dissipation stage of each thunderstorm region, the charge structure reverted to an inverted dipole or a normal dipole. (2) When the extent of the charge region expanded, the upper and lower charge regions became uneven and asymmetric. (3) In the inverted dipole charge structure, negative CG flashes accounted for 77.2% of the total number of lightning flashes, whereas negative intracloud flashes accounted for only 22.8%. In the tripole charge structure, negative CG flashes, positive intracloud flashes, and negative intracloud flashes accounted for 62%, 21%, and 16%, respectively, of all lightning flashes. These results indicate that the middle negative charge region was the strongest layer of the thunderstorm, while the upper positive charge region was slightly stronger, and the lower positive charge region was the weakest. These findings also indicate that the relative intensity of the charge layers directly determined the lightning quantity and frequency.

1. Introduction

The Qinghai-Tibet Plateau is the highest and the second largest plateau in the world. Under the action of the topography’s thermodynamics, thunderstorms are very frequent in summer. However, the duration of individual thunderstorms is short, and the lightning frequency of thunderstorms in this area is much lower than that in low-altitude and middle-latitude areas. Since the 1980s, Chinese scientists have conducted observational studies on thunderstorms occurring over the Qinghai-Tibet Plateau. The thunderstorms in this specific region were found to have a unique electrical structure and a large positive charge region often presented in the lower portion of the cloud. Liu et al. (1987) qualitatively inferred that thunderstorms on the Qinghai-Tibet Plateau have a tripole charge structure with a lower positive charge region that is widely distributed over a long span observed with a slow antenna and surface field mill. Shao and Liu (1987) determined several intracloud flash-neutralized charge sources in point-charge mode using the least squares method, and their results confirmed the existence of a tripole charge structure in the thunderstorms and revealed that the magnitude of the positive charge in the lower positive charge region was greater than that shown in a previous investigation (Jacobson & Krider, 1976). Subsequent studies have demonstrated that almost all intracloud flashes occur between the lower positive charge region and the middle negative charge region (Liu et al., 1989; Wang et al., 1990; Zhang et al., 2004). Qie et al. (2005) used surface field mills and fast and slow antennas to observe and analyze the evolution of a typical thunderstorm on the Qinghai-Tibet Plateau and suggested that intracloud flashes are normally composed of an inverted polarity and typically occur in the lower dipole of the tripole charge structure. The large lower positive charge region did not cause positive cloud-to-ground (CG) flashes to occur during the span of the whole storm; rather, only negative CG flashes were observed in the later stages of the storm. During the mature stages of a thunderstorm on the Qinghai-Tibet Plateau, thunderstorms with a tripole charge structure and a positive surface electric field
were found to be relatively abundant; conversely, thunderstorms with a negative surface electric field and a normal dipole charge structure were rare (Qie et al., 2009; Zhang et al., 2004).

In summary, early research on the charge structure of thunderstorms over the Qinghai-Tibet Plateau was based mainly on measurements of the surface electric field and electric field changes caused by lightning to fit the positions of charge sources neutralized by lightning discharges. Unfortunately, these measurements do not accurately fit every lightning result because surface electric field stations are affected by the topography and geographical environment; moreover, surface electric field measurements are affected by the shielding around the electric charge layer. In relation to the position of the charge region, only the approximate height of the charge source neutralized by lightning can be fitted; in contrast, the initial lightning discharge position and the location of the entire charge region cannot be described. Additionally, most of the results reported by these studies of surface electric fields and electric field changes were qualitative, whereas little detailed research has been performed on the region and position of the whole charge structure and the lightning discharge process between the upper positive charge and middle negative charge regions.

With the development of electronic technology, a lightning detection method, namely, the three-dimensional (3-D) lightning very high frequency (VHF) radiation source location system, has been developed (Thomas et al., 2004; Zhang et al., 2015). Since 2009, comprehensive observations of thunderstorms on the Qinghai-Tibet Plateau have been carried out by using the 3-D lightning VHF radiation source location system. Li et al. (2013, 2017) analyzed continuous observation data obtained using this location system to study the changes of the charge structure during the evolution of isolated and multicell thunderstorms on the Qinghai-Tibet Plateau, and their findings indicated that the charge structure maintains an inverted dipole for a significant period of time in the development and mature stages of isolated thunderstorms on the Qinghai-Tibet Plateau and that the charge structure exhibits a complex four-layer structure during the dissipation stage. The number of intracloud flashes was greater than the number of negative CG flashes during the evolution of the thunderstorms, and negative CG flashes did not occur completely in the dissipation stage. At the beginning of the development stage, each cell in the multicell thunderstorm developed as an isolated cell with a long-term inverted dipole, but in the dissipation stage, due to the merger between thunderstorm cells, a tripoles charge structure appeared, and multiple charge structures were observed to coexist. Intracloud and negative CG flash peaks appeared at different times, and the ratio of the intracloud flashes occurring between the upper positive charge and middle negative charge regions was high. Evidently, changes in the charge structure with the vertical development of thunderstorms have a significant influence on lightning activity, and the lightning type and quantity vary significantly throughout the evolution of the charge structure.

Previous research on thunderstorms over the Qinghai-Tibet Plateau has shown more intracloud flashes than CG flashes (Zhou et al., 2004), which is similar to the findings in other regions. For example, Wiens et al. (2005) analyzed a thunderstorm that occurred over northwestern Kansas in the United States, where intracloud flashes accounted for 95–100% of the total lightning activity during any given minute. As a unique characteristic, nearly 90% of the CG flashes were positive. These frequent positive CG flashes occurred in correlation with an inverted tripoles charge structure downwind of the hail core, and the presence of a lower negative charge region appeared to be a requirement for the positive CG flashes of this storm. Of course, the inverted tripoles charge structure occurred depending on the location of the particle collisions relative to the updraft; thus, the particles involved in the collisions were segregated by the wind flow based on their sizes and associated fall speeds. Most of the thunderstorms on the Qinghai-Tibet Plateau are dominated by intracloud flashes; that is, the quantity of intracloud flashes is often far greater than that of CG flashes. A detailed statistical analysis of thunderstorms on the Qinghai-Tibet Plateau revealed that thunderstorms exhibiting far more negative CG flashes than intracloud flashes rarely occur. Accordingly, in this paper, we analyzed an exceptional multicell thunderstorm with lightning flashes comprising 63.3% negative CG flashes and 35.1% intracloud flashes. The cloud base height (CBH) of this thunderstorm was about 1.4 km above the ground (AGL), and the height of the 0 °C layer was about 3.2 km (AGL). Previous statistics collected for the altitude of the 0 °C layer were mainly distributed in the 1.8–2.4 km (AGL) in summer of the Qinghai-Tibet Plateau (Huang et al., 2017). Qie et al. (2009) analyzed 11 thunderstorm processes on the Qinghai-Tibet Plateau and obtained an average CBH of about 1.1 km. Therefore, this thunderstorm is a special thunderstorm because of the dominant negative CG, higher 0 °C layer, and lower CBH. Then, 3-D lightning VHF radiation source location system data were used in conjunction with fast antenna and radar data to
analyze the evolution characteristics of this unique type of thunderstorm charge structure. The influences of the evolution of the thunderstorm charge structure on the lightning type and flash frequency were also discussed.

2. Data and Methodology

2.1. Observation Network and Thunderstorm Description

In this paper, a 3-D lightning VHF radiation source location system was used simultaneously with fast antenna and Doppler weather radar to observe a multicell thunderstorm that occurred in the Datong district of Qinghai on 27 July 2012. The observation network of the 3-D lightning VHF radiation source location system (Zhang et al., 2015) is located in Datong County, Qinghai Province, China, and consists of seven observation stations with altitudes ranging from 2.5 to 2.7 km. Six substations are radially distributed within 15 km around a central station (Mingde station). Each station is equipped with a 3-D lightning VHF radiation detection system with a working frequency range of 267–273 MHz. This system receives the radiation pulse signals produced by a lightning discharge and then measures the arrival times of the impulsive radiation event of the lightning discharge at each remote location using GPS technology; the peak value event resolution is 50 ns. The system dealt with one peak value event in successive 50-μs time windows, wherein the radiation source position for each peak value event was calculated using a nonlinear least squares method (Zhang et al., 2010). The location result can describe a 3-D image of the entire lightning discharge process for each flash. For radiation sources inside the network, the mapping system has a root-mean-square (rms) horizontal error of 12–48 m and an rms vertical uncertainty of 20–78 m. For radiation sources outside the network, the range and altitude errors increase as a function of the range squared (Zhang et al., 2015). In addition, each observation station is also equipped with a synchronized fast antenna. The bandwidth ranges from 1.5 kHz to 10 MHz, and the decay time constant is 100 μs. The waveform of the fast antenna is used in combination with the 3-D lightning VHF radiation source location system to ascertain the types of intra-cloud or CG flashes occurring within the thunderstorm. In addition, a new-generation C-band (5 cm) Doppler weather radar (CINRAD/CC) located 48 km from the central station provided simultaneous meteorological observations of the area. According to the development time of the thunderstorm, this paper used sounding data from the nearest Xining station (35 km from the central station) recorded at 20:00 (Beijing Time) on 27 July 2012. The height of the 0 °C layer was 3.2 km above the ground, and the convective available potential energy (CAPE) was 88 J/kg. The calculated cloud base height was 1.4 km (AGL). The distance and height used in this paper are based on the central Mingde observation station with the coordinates of E101.62°, N37.01° and an altitude (ground height) of 2.5 km. All recorded altitudes are given as heights above ground altitude (AGL).

During the multicell thunderstorm analyzed in this work, cells first occurred at 19:00 (Beijing Time) and then moved toward the southwest to merge with other cells to form the first main discharge region (Region 1). At 21:13, other cells merged to form the second main discharge region (Region 2) and then underwent multiple mergers and splitting processes within the two discharge regions. The lightning frequency changed as the thunderstorm developed, with the storm finally dissipating at 23:05 (i.e., no further lightning was generated). A total of 706 lightning flashes occurred during this multicell thunderstorm, including 248 intracloud flashes accounting for 35.1% of all lightning flashes, 447 negative CG flashes accounting for 63.3%, and only 11 positive CG flashes accounting for 1.6%. The entire evolution process of the thunderstorm was within the effective detection range of the lightning location network.

2.2. Determination and Definition of the Thunderstorm Charge Structure

The determination of the thunderstorm charge structure in this work is based mainly on the 3-D spatiotemporal evolution data of lightning discharges gathered by the 3-D lightning radiation source location system (Li et al., 2013, 2017). According to the bidirectional leader model, a lightning discharge initiates in the strong electric field that occurs between layers of net positive and negative charges and then propagates in opposite directions from the discharge origin to produce a negative breakdown and a positive breakdown, respectively, at its two fronts (Kasemir, 1960; Mazur & Ruhnke, 1993). By analyzing the transmission mode and spatiotemporal distribution characteristics of the lightning discharge channel, the polarity of the charge layer can be determined; in other words, the negative polarity breakdown of lightning generates stronger VHF radiation than the positive polarity breakdown. Thus, the negative polarity breakdown produces far

10.1029/2019JD031129
more VHF radiation sources in the positive charge region than the number of sources in the negative charge region produced by the positive polarity breakdown, and negative polarity breakdown occurs mainly within the positive charge region (Shao & Krehbiel, 1996; Rison et al., 1999). To determine the negative charge region, this work assumes that the negative leaders retrace the path of the quieter positive leader. Mazur and Ruhnke (1993) described how this retracing of the positive leader channel by the negative breakdown seems to correspond to the recoil leaders. The above method and principle of using a VHF lightning radiation source location system to determine the positive and negative charge regions are the same as those of using a lightning mapping array (LMA) system (Krehbiel et al., 2000; MacGorman et al., 2008; Rison et al., 1999; Rust et al., 2005). In the most recent research, Wu et al. (2016) used the 3-D lightning VHF radiation source location system synchronously with broadband electric field observations to ascertain that the polarity of the pulse cluster generated by lightning’s initial preliminary breakdown process corresponds well with the vertical transmission direction of the initial breakdown that originates from the negative charge region and develops into the positive charge region. The initial breakdown transmission direction can determine the vertical development direction of the initial preliminary breakdown, whose vertical development direction is related to the thunderstorm charge structure; consequently, the polarity of the pulse cluster generated by the initial preliminary breakdown process can also help to determine the polarity of the charge layer. Therefore, the abovementioned method can be used to judge the charge layer polarity and height of a single lightning flash. Then, the cumulative radiation source distribution characteristics taken from successive lightning discharges over a given time interval can be used to determine the dominant charge structure of the thunderstorm and the height of the charge regions participating in the lightning discharge.

To properly discuss the evolution of the thunderstorm charge structure at different stages of thunderstorm development, the charge structures observed during the thunderstorm evolution process must first be defined. The charge structure in this paper is composed of the participating lightning discharge region. Charge structures with only upper negative and lower positive charge regions are called inverted dipole charge structures. Normal dipole and tripole charge structures follow the convention of atmospheric electricity. According to the definition of a dipole charge structure developed by Bruning et al. (2014) and Zhang et al. (2014), the upper two charge layers of a normal tripole charge structure are referred to as the positive dipole structure, and the intracloud flashes produced between them are called positive intracloud flashes. Similarly, the lower two layers of a normal tripole charge structure are referred to as a negative dipole structure, which produces intracloud flashes called negative intracloud flashes. In addition, intracloud flashes that occur in an inverted dipole charge structure are classified as negative intracloud flashes, and intracloud flashes that occur in a normal dipole charge structure are classified as positive intracloud flashes.

The charge structure and position of the lightning discharge radiation source were obtained by 3-D lightning VHF location data. The type of lightning discharge (positive cloud flash, negative cloud flash, negative CG flash, and positive CG flash) was determined by the thunderstorm charge structure. The ratios of the number of different lightning discharge types occurring between the different charge regions were used to characterize and analyze the changes in the charge region’s relative intensity.

3. Analysis of the Thunderstorm Charge Structure and Lightning Type and Frequency

Strong thunderstorms exhibit an evolutionary process consisting of multicell growth, merging, splitting, and dissipation. Using the thunderstorm evolution observed through radar echo, we divide the two strong central echo zones that occurred during the storm on 27 July 2012 into thunderstorm Regions 1 and 2. Statistics on the frequency of each lightning type during the evolution of each cell are given for each radar volume scan interval (6 min). The following describes the correlation between the charge structure evolution and the corresponding lightning type and frequency during each stage of the evolution of the two thunderstorm regions and of each cell within those regions.

3.1. Cell Charge Structure and Discharge Characteristics

The initial development stage of the multicell thunderstorm analyzed in this work was composed of several relatively isolated cells, with each cell displaying its own development path and charge structure. The thunderstorm starts at 19:08 when Cell 1 first appears and moves from the east side of the measurement net to the southwest and lasts approximately 37 min until 19:45. Figure 1 shows that between 19:08 and 19:45, Cell 1...
produces 35 flashes and there are far more negative CG flashes than negative intracloud flashes. Figure 2 shows the lightning radiation source distribution of Cell 1. The charge structure of Cell 1 is an inverted dipole, and this charge structure lasts for approximately 38 min. Figure 3a displays the vertical cross section of Cell 1 at 19:45 corresponding to Figure 2a, and this figure shows that the intensity of the Cell 1 echo center reaches a maximum of approximately 55 dBZ and that the height of the 45 dBZ echo region reaches 6.5 km (AGL). Combining Figures 2a and 3a indicates that the upper negative charge region is at a height of 4.5–6.0 km (AGL) and is associated with a radar reflectivity of less than 45 dBZ; moreover, the lower positive charge region is at 2–4 km (AGL) and is associated with a radar reflectivity between 40 and 55 dBZ. Figure 4b shows the changes of the radar echo value with time. The figure shows that the maximum heights of different echo values increase after 19:26 and that the lightning frequency also begins to increase, indicating that the updraft in the thunderstorm strengthens and causes the lightning frequency of the cell to increase. Cell 2, which appears at 19:20, produces relatively few lightning flashes (only six flashes during its entire existence), all of which are negative CG flashes (Figure 1). The charge structure of Cell 2 is also an inverted dipole, and the height distribution is essentially the same as that of Cell 1. The merging of these two cells (Cells 1 and 2) at 19:51 forms thunderstorm Region 1.

In addition, a new cell (Cell 3) appears in the northern part of Region 1 at 20:16 (Figure 5d) and has only a short duration. Eight lightning flashes are generated during the development of Cell 3 (Figure 1), with more negative CG flashes than negative intracloud flashes occurring. As the lightning radiation source distribution shows, the charge structure is also an inverted dipole (Figure 2b). The negative charge region of Cell 3 is at a height of 4–5 km (AGL), and the lower positive charge region is at a height of 3–4 km (AGL). Figure 3b shows that the height of the 45-dBZ echo region in this cell reaches only 4.5 km (AGL) and the area of the 45-dBZ echo region is relatively small at 20:16. A comparison of the lightning radiation sources shown in Figure 2b and the radar echo shown in Figure 3b demonstrates that the lightning radiation sources are distributed mainly in the echo region, with an intensity of less than 45 dBZ. The cell essentially dissipates by 20:35, as it fails to merge into Region 1.
3.2 Charge Structure Evolution and Discharge Characteristics of Thunderstorm Region 1

3.2.1 First Merger

At 19:51, Cells 1 and 2 merge to form Region 1, indicating the beginning of a new stage in the evolution of the thunderstorm (the first evolution cycle). As the storm develops through the 19:58–20:23 period, the lightning type and frequency change. As shown in Figure 4a, positive intracloud flashes appear, and the number of positive intracloud flashes increases rapidly. Figure 4b also shows that the height of the radar echo began to ascend obviously. The negative CG flash frequency also increases. The first frequency peaks of the negative CG flashes and positive intracloud flashes both occur at 20:10, with far more negative CG flashes than intracloud flashes occurring but with positive intracloud flashes remaining more common than negative intracloud flashes. The frequency and type of lightning flashes and the charge region distribution indicate that the upper positive charge region becomes strengthened while the middle negative charge region stays the strongest. The appearance of the upper positive charge region indicates that the charge structure changes from an inverted dipole structure of cells to a tripole structure. As Figures 5Aa–5Ae shown, thunderstorm Region 1 continues to show expansion in the echo zone with intensities greater than 45 dBZ after the merging of Cells 1 and 2. In comparing the radiation source distribution (Figure 6a) with the corresponding...
Figure 5. (A) The radar composite reflectivity from 19:58 to 21:56 for the thunderstorm on 27 July 2012. (B) Corresponding lightning radiation sources from 19:58 to 21:56 for the thunderstorm on 27 July 2012 overlain atop the radar composite reflectivity and charge structure. The pink “.” symbols in each image are the radiation sources. The dotted line is the radar echo cross-section position.
vertical cross section of the radar echo intensity (Figure 7a) during this period, the upper positive charge region rises from the original height of 6–8 km to a height of 7.5–10 km (AGL) (Figure 6a) and is associated with radar echo intensities between 20 and 40 dBZ. The middle negative charge region is located at a height of 4.5–6 km (AGL) and is associated with radar echo intensities between 40 and 55 dBZ, while the lower positive charge region is located at a height of 2.5–4.5 km (AGL) and is associated with radar echo intensities

Figure 6. The charge structure distributions of the lightning radiation sources of Region 1 in different directions following the same format as that in Figure 2.

Figure 7. Vertical cross sections of the radar reflectivity of Region 1 at 20:10, 21:00, 21:25, and 21:56. The radar echo cross-section positions corresponding to the dotted lines that are in Figures 5Bc, 5Bk, 5Bo, and 5Bt, respectively.
Figure 8. (A) The radar composite reflectivity from 22:03 to 22:53 for the thunderstorm on 27 July 2012. (B) Corresponding lightning radiation sources from 22:03 to 22:53 for the thunderstorm on 27 July 2012 overlain atop the radar composite reflectivity and charge structure. The pink “.” symbols in each image are the radiation sources. The dotted line is the radar echo cross-section position.
between 40 and 60 dBZ. Compared with the height of the echo region before the cell merger, the heights of the 20- to 40-dBZ echo regions increase (Figure 4b), indicating that the updraft becomes enhanced after the merger, after which the upper positive charge region appears, and all the charge regions are elevated. Figure 7a also shows the strong vertical development of a mixed-phase region, which promotes the production of positive intracloud flashes.

During the thunderstorm development interval from 20:29 to 20:35, the number of lightning flashes rapidly decreases, entering the first frequency valley (Figure 4a). The thunderstorm as a whole weakens, and the height of the charge region descends, although the charge structure still maintains a weak tripole structure; nevertheless, this stage of the storm is ending. The radar echo intensity of thunderstorm Region 1 begins to weaken, and the strong echo area decreases at this time. These changes mean that the updraft is weakened and the frequency of lightning flashes is decreased. During this round of evolution of the thunderstorm region, the tripole charge structure is maintained for 48 min.

### 3.2.2. Second Merger

During the interval of 20:41–20:54, the strong echo zone with intensities larger than 45 dBZ in Region 1 further reduces, and a new cell is generated. Then, the dissipated and newly generated cells gradually merge (Figures 5Ah–5Aj), and the frequency of negative CG flashes increases rapidly (Figure 4a). At 21:00, the positive intracloud flash frequency begins to increase (Figure 4a). The charge structure of Region 1 completely changes from an inverted dipole structure to a tripole structure. The charge layer distributions illustrated in Figures 6b1 and 6b2 and the corresponding radar echo vertical cross section in Figure 7b show that the upper positive charge region is distributed at a height of 7–9 km (AGL) and is associated with radar echo intensities between 20 and 35 dBZ, the middle negative charge region is at 4–7 km (AGL) and is associated with radar echo intensities between 30 and 45 dBZ, and the lower positive charge region is located at 2–3.5 km (AGL) and is associated with radar echo intensities between 30 and 55 dBZ. Figure 7b shows that the height of the 45-dBZ echo region in the newly generated cell on the left side reaches 6 km (AGL) at this time and the 20-dBZ echo region reaches 9 km (AGL), while the radar echo region in the original cell on the right side of Region 1 is weak. This indicates that the region of the newly generated cell is characterized by strong convection and that the original cell possesses weak convection. Therefore, the charge region position is higher in the newly generated cell than in the original cell (Figure 6b1). Furthermore, the strong convection enlarges the area of strong radar echoes, and the horizontal scale of the negative charge region becomes enlarged at this time. This may have promoted more negative CG production in this stage. Within the 6-min interval at 21:06, the cell on the left side in Region 1 produces only positive intracloud flashes (Figure 5Bl). The second small peak of the positive intracloud flash frequency appears, marking the first time that the positive intracloud flash frequency is greater than the negative CG flash frequency in a given 6-min interval during the thunderstorm Region 1 development process.

At 21:13, although the two cells in Region 1 completely merge (Figure 5Bm), Region 1 begins to dissipate. At this time, the negative CG flash frequency far exceeds the intracloud flash frequency and increases even more to the second small frequency peak (Figure 4a). As the thunderstorm develops through the period of 21:19–21:31, the lightning frequency drops into the second frequency valley. Most lightning flashes occur between the middle negative charge and upper positive charge regions, and the number of positive intracloud flashes exceeds the number of negative intracloud flashes and negative CG flashes. This marks the second time that the positive intracloud flash frequency is greater than the negative CG flash frequency during the development process of thunderstorm Region 1 (Figure 4a). However, the storm region still maintains a tripole charge structure, and the storm’s charge region height begins to tilt from west to east. As shown in Figures 6c1 and 6c2, the charge region height declines from 3–8 km (AGL) to 2–6 km (AGL). During this period, thunderstorm Region 1 splits, the 45-dBZ echo zone shrinks, and the echo intensity gradually decreases (Figures 5Ao and 5Ap). Furthermore, the overall charge region height slightly decreases. As Figure 7c shows, the upper positive charge region shifts to a height of 5–7 km (AGL), the middle negative charge region shifts to a height of 3–5 km (AGL) and is associated, and the lower positive charge region height decreases to 2–3 km (AGL). Figure 7c also shows that the heights of the 45- and 20-dBZ echo regions decrease to 4 km (AGL) and 8 km (AGL), respectively. This result illustrates that a decrease in the radar echo intensity is correlated with reduced updraft speed, causing the height of the charge region to descend. Region 1 continues to weaken through the following interval at 21:38 (Figure 5Bq), and the charge structure changes from a tripole to an inverted dipole, and the echo zone intensity corresponding to the charge region drops to...
less than 40 dBZ. At this time, the frequencies of negative CG flashes and negative intracloud flashes begin to increase (Figure 4a) as the thunderstorm enters the next phase of its evolution.

### 3.2.3. The Third Merger

As the thunderstorm develops through the 21:44–21:50 interval, the development of thunderstorm Region 2 also continues, and some portions of Region 2 merge into Region 1 (Figures 5Ar and 5As). At this point, the negative CG flash and positive intracloud flash frequencies both increase again, and the negative intracloud flash decreases. This may result from the gradual enhancement of the updraft during the merging of these storm areas. The charge structure of Region 1 changes from an inverted dipole to a tripole charge structure.

At 21:56, the negative intracloud flash frequency increases rapidly to a slightly higher frequency than those of the negative CG flashes and positive intracloud flashes, with the positive intracloud flash frequency being the lowest (Figure 4a). At this time, as shown in Figure 7d, the echo center intensity increases to 55 dBZ, and the height reaches about 5 km. The area of the >40-dBZ echo zone expands. The heights of the 20- and 40-dBZ echo regions increase, but they do not reach a maximum. Upon comparing Figures 6d and 7d, near the central part of the strong echo zone, the upper positive charge region is clearly located between 6 km (AGL) and 9 km (AGL) and is associated with radar echo intensities between 20 and 40 dBZ, while the middle negative charge region is located between 4 km (AGL) and 6 km (AGL) and is associated with radar echo intensities between 30 and 50 dBZ. Moreover, the charge structure is dominated by a positive dipole charge structure. This means that the strong updraft causes the strong development of a mixed-phase region. In the region far from the central part of the strong echo zone, the height of the negative charge region conforms to the height of the strong echo zone region. The lower positive charge region is located between 2 km (AGL) and 4 km (AGL) and is associated with radar echo intensities of less than 40 dBZ, and the charge structure is a negative dipole. Figure 6d shows that the distributions of the upper and lower positive charge regions are uneven and asymmetrical, but the thunderstorm charge structure as a whole still exhibits a tripole structure. The above analysis also indicates that the area of the 45-dBZ echo zone increases and that the heights of the 45- and 20-dBZ echo zones rise with enhanced updraft. This strong updraft is conducive to the appearance and enhancement of the upper positive charge region. In contrast, the convection along the periphery of the echo zone with intensities of less than 45 dBZ is weak, and the charge structure presents only an inverted dipole. Therefore, the distributions of the upper and lower positive charge regions become uneven and asymmetrical.

During the period of 22:03–22:46, Region 2 continues to strengthen (as described in the next section) and merges more deeply with Region 1, thereby increasing the speed of the enhancement of Region 1 (Figures 8Aa–8Ah). The positive intracloud flash frequency reaches its third peak at 22:09. However, the negative CG flash frequency is the highest during this period, reaching its third frequency peak at 22:21, later than the peak frequency of the positive intracloud flash. We analyzed the radiation source distribution and radar echo during 22:09–22:21 (Figures 9a–9c and 10a–10c). The results indicate that the upper positive charge region rises to 7–10 km (AGL) and is associated with radar echo intensities between 20 and 40 dBZ, while the middle negative charge region rises to 5–7 km (AGL) and is associated with radar echo intensities between 30 and 50 dBZ, and the lower positive charge region rises to a height of 2–4.5 km (AGL) and is associated with radar echo intensities between 40 and 55 dBZ. As shown in Figure 4b, the height of the 40-dBZ echo zone reaches 8 km (AGL) during this period, and the height of the 20-dBZ echo zone reaches 11 km (AGL). Compared with those at 21:50, the heights of the 40- and 20-dBZ echo zones increase. Note that the height of the upper positive charge region reaches its maximum of 10 km (AGL) at this time, and the frequency of lightning flashes also reaches its maximum (Figures 4a and 9a–9c). At 22:28, as shown in Figure 4b, the height of the 20-dBZ echo region descends to 10 km (AGL), and the echo top also descends. At this time, the frequencies of negative CG flashes and negative intracloud flashes begin to decrease, and there are relatively few positive intracloud flashes. In summary, during the overall period covered by Figure 10, the height of the echo region ascends, which means that convection is enhanced, and the entire charge region is also elevated considerably. The frequency of lightning flashes increases, especially the frequency of positive intracloud flashes, increases rapidly. When the heights of the 20-dBZ echo region and echo top descend, convection weakens, and the frequency of lightning flashes begins to decrease. During the period of 22:03–22:46, the negative CG flash frequency is much higher than the positive intracloud flash frequency, and the positive intracloud flash frequency is much higher than the negative intracloud flash frequency (Figure 4a). Figure 4b shows that the radar echo values ascend and reach the maximum height,
which is maintained for a long time during the third merger process. This indicates that the mixed-phase region develops vertically under the action of the strong updraft, accelerates the separation of charge particles, and promotes the enhancement of the upper positive charge region and the middle negative charge region. As the upper positive charge region is higher from the ground and the middle negative charge region is strong, the positive leader has difficulty reaching the ground to generate a positive CG. Therefore, more positive intracloud flashes occur between the upper positive charge region and middle negative charge region. Because the lower positive charge region is weak and small relative to other two charge regions and the distance from the negative charge central to the ground is short, the negative

Figure 9. The charge structure distributions of the lightning radiation sources of Region 1 in different directions from 22:09 to 22:28 following the same format as that in Figure 2.

Figure 10. Vertical cross-sections of the radar reflectivity of Region 1 at 22:09, 22:15, 22:21, and 22:28. The radar echo cross-section positions corresponding to the dotted lines that are in Figures 8Bb, 8Bc, 8Bd, and 8Be, respectively.
leader of downward development can easily pass through the lower positive charge region to the ground and form a negative CG. This result indicates that the middle negative charge region is very powerful and the upper positive charge region is stronger than the lower positive charge region at this time. In summary, this third merger process was the strongest lightning-producing process during the thunderstorm, as the tripole charge structure was maintained for a maximum of 66 min.

After 22:46, the height of the charge region gradually descends with the dissipation of the thunderstorm, at which point the positive charge region is distributed mainly at heights of 4–6 km (AGL), and the negative charge region is distributed between 2 and 4 km (AGL). The lightning frequency rapidly decreases as the charge structure shifts to a normal dipole structure. In particular, no negative intracloud flashes occur, indicating that the lower positive charge region likely no longer exists. The echo intensity of the thunderstorm (Region 1) is already weakened. The height of the 40-dBZ echo zone decreases to 5 km (AGL), and that of the 20-dBZ echo zone decreases to 8 km (AGL). This indicates that the thunderstorm dissipates quickly and that the updraft no longer exists. The downdraft may make the lower big positively charged particles drop off and no longer participate the lightning, such that the lower positive charge region disappears. No further development of the thunderstorm occurs after 23:05; that is, the evolution of the thunderstorm in Region 1 ceases.

Based on the above analysis, we can see that cells independently existed and developed during the initial evolution of the storm region, where each cell maintained an inverted dipole charge structure during its initial development stage. The negative CG flash frequency and negative intracloud flash frequency were dominant when the storm possessed an inverted dipole charge structure, and the negative CG flash frequency was higher than the negative intracloud flash frequency.

The merging of cells increased the potency of the thunderstorm in the mature stage, during which the area of the echo zone with intensities larger than 40 dBZ expanded and the heights of the 40- and 20-dBZ echo regions increased. During this stage, the charge structure changed to a tripole structure. For the lightning flashes, the negative CG flash frequency and the positive intracloud flash frequency were dominant, and the negative CG flash frequency and positive intracloud flash frequency also exhibited three peaks. However, negative CG flashes were much more frequent than were positive intracloud flashes, and positive intracloud flashes were far more frequent than were negative intracloud flashes. This illustrates that the enhanced convection made the upper positive charge region appear and participate in the discharge process, causing the inverted dipole charge structure to change to a tripole charge structure. Meanwhile, the enhanced convection made the height of the negative charge region lifted and enlarged the area of the negative charge region. Therefore, the negative charge region became stronger than before. With the weak effect of the lower positive charge region, an abundant negative CG was produced. The storm maintained its tripole charge structure for 156 min during these three evolutionary periods, while all the charge regions reached and maintained the highest altitude in each evolutionary period.

During the dissipation and splitting processes at the end of the storm, the merged cell became an inverted dipole structure once again. The area of the echo regions with intensities of larger than 40-dBZ shrunk, and the heights of the echo regions with intensities of larger than 40 and 20 dBZ decreased. This means that the downdraft caused the thunderstorm dissipation. However, the charge structure during the third period became a normal dipole structure due to the rapid disappearance (after 6 min) of the lower positive charge region, which lasted until the thunderstorm completely dissipated.

For Cell 3, we can see that the cell maintained only an inverted dipole charge structure throughout the storm and dissipated within a short period of time because the cell did not merge with Region 1. The area of the >40-dBZ echo region was small, and the height of the 40-dBZ echo region reached only 5 km (AGL).

### 3.3. Charge Structure Evolution and Discharge Characteristics of Thunderstorm Region 2

Thunderstorm Region 2 formed through the merger of Cells 4 and 5. Isolated Cell 4 appears at 20:29 in the northwestern sector of the observation station network (Figure 5Af). The lightning produced at 20:48 displays an inverted dipole charge structure (Figures 11 and 12a). This charge structure lasts for approximately 24 min, during which developing downward negative CG flashes dominate the interval with a frequency far greater than that of negative intracloud flashes (Figure 11). Although the height of the 45 dBZ echo region reaches 6 km (AGL) at 20:48 (Figure 13a), the area of the 45-dBZ echo region is small (Figure 5Ah). Figure 12...
a shows that the negative charge region has a height of 4.5–6 km (AGL) and a positive charge region at 2.5–4.5 km (AGL). Comparing the results with Figure 13a, the radiation sources are distributed in the 20- to 45-dBZ echo region. Cell 5 forms later than Cell 4 at 20:41 (Figure 5Bb) and is weaker than Cell 4, producing a lightning flash after 6 min. Cell 5 also displays an inverted dipole charge structure, as shown in Figure 12b, which is maintained for 18 min. The charge layer distribution of Cell 5 shows that the negative charge region is at a height of 4–6 km (AGL), while the positive charge region is at 2–4 km (AGL). At 21:06, the height of the 45-dBZ echo region is approximately 6.5 km (AGL) (Figure 13b), but the area of the 45-dBZ echo region is relatively small (Figure 5AI). The radiation sources are distributed mainly in the 15- to 55-dBZ echo region. At 21:13, Cells 4 and 5 begin to merge. At this time, the lightning leaders from the negative charge region of Cell 4 are transmitted upwards into the upper positive charge region and produce positive intracloud flashes. The charge structure quickly changes into a tripoles charge structure with an upper positive charge region height of 7–9 km (AGL). During the same interval, Cell 5 also changes into a tripoles charge structure, but it possesses an upper positive charge region height of only 6–8 km (AGL), which is slightly lower than that of Cell 4. Furthermore, Cells 4 and 5 each produce only two positive intracloud flashes during this interval, while the frequency of negative CG flashes increases rapidly (Figure 11). Developing negative CG flashes continue to dominate, and the frequency of negative CG flashes is always greater than the frequency of intracloud flashes.

After the merger of Cells 4 and 5, the negative CG flash frequency gradually increases over this period, eventually reaching its peak (Figure 11a), and the negative CG flash frequency remains much higher than the intracloud flash frequency during the period of 21:19–21:38. In addition, the positive intracloud flash frequency is far more than the negative intracloud flash frequency, and the region maintains a tripoles charge structure (Figure 14a). As Figure 5Am shows, two strong echo centers appear in thunderstorm Region 2 after

![Figure 11](image-url)  
**Figure 11.** Evolution of the lightning flash frequency for Cells 4 and 5 and thunderstorm Region 2 by lightning type per radar volume scan interval over the period of 19:08–23:05. In the figure, −IC, +IC, NCG, and IC indicate negative intracloud flashes, positive intracloud flashes, negative CG flashes, and intracloud flashes, respectively. (b) The height changes of the radar reflectivity with time in Region 2.

![Figure 12](image-url)  
**Figure 12.** The charge structure distributions of the lightning radiation sources of Cells 4 and 5 in Region 2 in the west-east direction following the same format as that in Figure 2.
the merger of Cells 4 and 5. These two strong echo centers gradually merge and increase in strength, and the generated lightning flashes are distributed around the two centers (Figures 5An–5Aq and 5Bn–5Bq). Over this period, as shown in Figures 5Bn–5Bq, the area of the >40-dBZ echo zone gradually increases, and the height of the 40-dBZ echo zone reaches 8 km (AGL) (Figure 11b), whereas the height of the 20-dBZ echo zone reaches 12 km (AGL). Figures 14a and 15a show that the upper positive charge region is located at a height of 7–9 km (AGL) and is associated with radar echo intensities between 20 and 40 dBZ, while the middle negative charge region is located at 4–6 km (AGL) and is associated with a radar echo intensity of 45 dBZ, and the lower positive charge region is located at 2–4 km (AGL) and is associated with radar echo intensities between 40 and 55 dBZ. Evidently, the height of the radar echo region increases with enhanced convection, the frequency of lightning flashes increases, and the frequency of positive intracloud flashes is larger than that of negative intracloud flashes.

The thunderstorm region continues to develop through the period of 21:44–22:03, during which the negative CG flash frequency maintains its maximum value in Region 2 (Figure 11a), and the negative CG flash frequency remains much higher than the intracloud flash frequency. However, the numbers of positive and negative intracloud flashes change significantly over this period, with the latter becoming more common.
than the former. At this time, Region 1 also begins to gradually merge into Region 2 (Figure 5At). As the two strong echo centers of Region 2 merge more thoroughly, the area of the echo zone with intensities larger than 40 dBZ expands, but the height decreases slightly (Figure 11b), while the height of the 20-dBZ echo zone is maintained at 10 km (AGL). The charge structure of Region 2 continues to exhibit a tripole charge structure, with the upper positive charge region at a height of 7–9 km (AGL) corresponding to a radar echo zone with intensities of 20–40 dBZ, the negative charge region at 4–7 km (AGL) corresponding to a radar echo zone with intensities of 30–45 dBZ, and the lower positive charge region at 1.8–4 km (AGL) corresponding to a radar echo zone with intensities of 35–50 dBZ (Figures 14b–14d and 15b). The echo intensity is less than 40 dBZ outside the strong echo zone where lightning occurs. The change in the frequency of lightning flashes and in the charge region illustrate that the upper and lower positive charge regions are relatively weak during this period, whereas the middle negative charge region is very powerful. However, the lower positive charge region becomes stronger than the upper positive charge region.

In comparing the periods of 21:19–21:38 and 21:44–22:03, when the area of the >40-dBZ echo zone broadens and the heights of the 40- and 20-dBZ radar echo regions increase, the convection becomes enhanced, increasing the frequency of lightning flashes, and the frequency of positive intracloud flashes becomes higher than that of negative intracloud flashes. When the height of the 40-dBZ echo region decreases, the radar echo intensity of the lower part of the thunderstorm becomes large. The middle negative charge and lower positive charge regions become thick, the frequency of negative CG flashes reaches its peak, and the frequency of negative intracloud flashes becomes higher than that of positive intracloud flashes.

Subsequently, the intensity of thunderstorm Region 2 gradually weakens, the heights of the radar echoes descend gradually (Figure 11b), and the thunderstorm region splits. At 22:09, the frequency of negative CG flashes rapidly decreases but still maintains a frequency that is higher than that of intracloud flashes. During the period of 22:15–22:28, Region 2 enters a slow dissipation phase in which lightning flashes...
become very rare, and again, negative CG flashes dominate with a greater frequency than that of intracloud flashes (Figure 11). The region also maintains a tripole charge structure.

During the interval of 22:34–22:40, Region 2 dissipates further. The lightning flashes become dominated by negative intracloud flashes, which are more common than positive intracloud flashes over this period, while the number of negative CG flashes decreases to zero. The charge region angles downward from west to east, and the upper and lower positive charge regions become asymmetrical (Figures 14e and 14f). During this period, the height of the 40-dBZ echo zone drops to 4 km (AGL), and the height of the 20-dBZ echo zone drops below 8 km (AGL), as shown in Figure 11b. Comparing the radiation source distributions and vertical radar echo cross sections (Figures 14c, 14f, 15c, and 15d) reveals that the upper positive charge region is mainly distributed at heights of 6–8 km (AGL) and is associated with radar echo intensities between 20 and 40 dBZ, while the middle negative charge region is between 4–6 km (AGL) and associated with radar echo intensities between 30 and 40 dBZ, and the lower positive charge region is distributed mainly between 2 and 4 km (AGL) and is associated with radar echo intensities between 30 and 45 dBZ. The lightning produced with a weak echo corresponds to the echo zone with an intensity of less than 40 dBZ. The number of each type of lightning flash and the changes in the radar echo indicate that the lower positive charge region is stronger than the upper positive charge region and that the middle negative charge region becomes weak in Region 2 during the interval of 22:34–22:40. That is, the overall height of the charge region and strong echo zone decreases over this period.

Thunderstorm Region 2 enters a stage of rapid dissipation after 22:46, in which the charge structure changes from a tripole to an inverted dipole and the overall height of the charge region continues to decrease. Lightning flashes become very infrequent, with the number of negative CG flashes dropping to almost zero. At 22:59, the region merges with the dissipated remains of Region 1, and there is no further development. At 23:05, the entire thunderstorm process ceases.

This analysis of the evolution of thunderstorm Region 2 indicates that its process was essentially the same as that of Region 1. In other words, each thunderstorm region started with the generation of multiple cells in the initial stage; the subsequent merging of cells strengthened each thunderstorm region in its mature stage, and the thunderstorms split apart and weakened in the dissipation stage. The corresponding charge structure for each region was an inverted dipole in the initial stage, which changed into a tripole charge structure in its strongest mature stage and then returned to an inverted dipole in the dissipation stage. The types of lightning flashes were dominated by negative CG flashes throughout the entire development process of thunderstorm Region 2. The echo intensity increased because of the merging of multiple cells in Region 2. As the two strong thunderstorm centers continued to merge in Region 2, the >40-dBZ echo zone expanded, and the height of the 40-dBZ zone reached 7 km (AGL). The frequency of negative CG flashes reached its peak; at this time, the frequency of positive intracloud flashes was greater than that of negative intracloud flashes. Then, the height of the 40-dBZ echo zone gradually decreased, and the area of the >40-dBZ echo region expanded, while the height of the 20-dBZ echo region remained at 10 km (AGL). The changes of the radar echoes indicate that the updraft in Region 2 started to weaken and the upper positive charge area became weakened. However, the vertical development of the mixed-phase region under the influence of the updraft still exerted a strong effect on the lightning discharge between the lower positive charge region and the middle negative charge region, with the middle negative charge region still maintaining enhancement. As a result, the frequency of positive intracloud flashes decreased, while that of negative intracloud flashes increased to the point at which the frequency of negative intracloud flashes was greater than that of positive intracloud flashes, but negative CG flashes were much more frequent than intracloud flashes. The above results indicate that the vertical development of the mixed-phase region in the thunderstorm was mainly controlled by the updraft, which had a direct influence on the configuration of the different charge regions. The tripole charge structure was maintained for more than 90 min in Region 2. As the thunderstorm began to end, the lightning frequency decreased rapidly, and the overall heights of the charge region and >40-dBZ echo zone decreased. As the charge structure shifted to an inverted dipole charge structure, the height of the charge region decreased with the weakening of the thunderstorm, and the number of negative intracloud flashes dropped to almost zero. At this point, there was no new development in the thunderstorm, indicating that the thunderstorm was almost finished.
The difference between Regions 2 and 1 is that Region 2 underwent only one evolution cycle (weak, strong, and then weak). The heights of the radar echoes in Region 1 are higher than those in Region 2. These characteristics mean that the updraft in Region 2 was weaker than that in Region 1. The number of negative CG flashes in Region 2 was the highest, and the number of negative intracloud flashes was slightly higher than that of positive intracloud flashes. This indicates that the lower positive charge region was stronger than the upper positive charge region and the middle negative charge region was strongest in thunderstorm region 2.

4. Results

4.1. Statistical Characteristics of the Lightning Type and Frequency

In this work, the lightning type was determined according to the lightning channel and initial preliminary breakdown development direction obtained through a 3-D lightning VHF radiation source location system in combination with the pulse polarity of the initial preliminary breakdown process and the waveform obtained from synchronous fast antenna observations. The lightning flashes during the evolution processes of the thunderstorms were classified, and the statistics concerning the frequency of each lightning type were analyzed. For a storm with a tripole charge structure, intracloud flashes can be divided into three types. Positive intracloud flashes and negative intracloud flashes are described in section 2.2. When a positive intracloud flash occurred, followed by a negative intracloud flash, with a connecting channel between them, this was termed a hybrid intracloud flash. Another type of hybrid intracloud flash includes when a negative intracloud flash first occurs, followed by a positive intracloud flash, with a connecting channel between them. The hybrid intracloud flash is called a Type III intracloud flash (Figure 16).

Similarly, the negative CG flashes that occurred in the tripoole charge structure of the thunderstorm regions studied in this work were divided into three categories. As shown in Figure 17, negative CG flashes that occur directly in the inverted dipole charge structure are classified as a Type I negative CG flash, while negative CG flashes generated by the normal dipole charge structure are a Type II negative CG flash. Although Type III negative CG flashes actually have three subtypes (Wu et al., 2016), Type III negative CG flashes are distinguished by the fact that the discharge occurs between the three charge layers.

Each lightning flash during the thunderstorms studied in this work was classified with respect to its charge structure evolution, quantity, and frequency. It should be noted that positive CG flashes were very infrequent and, thus, they were not studied in depth. Moreover, Cell 3 did not merge into Region 1, and flashes in Cell 3 were infrequent; hence, the flashes in Cell 3 were not counted. The statistical results of Cells 1, 2, 4, and 5 and Regions 1 and 2 are shown in Tables 1–3. The following analysis correlates the number of each type of lightning flash according to the different charge structures of the thunderstorm and its evolution. Additionally, the quantity of each lightning flash type in the tripoole charge structure between Regions 1 and 2 was compared and analyzed.

As Tables 1–3 and Figure 18 shown, in the inverted dipole charge structure, negative CG flashes accounted for 77.2% of the total number of lightning flashes, while negative intracloud flashes accounted for only 22.8%. In the tripoole charge structure, negative CG flashes, positive intracloud flashes, and negative intracloud flashes accounted for 62%, 21%, and 16%, respectively, of the total number of lightning flashes. Over the full span of the thunderstorm, the number of negative CG flashes far exceeded the number of intracloud flashes, and the number of positive intracloud flashes was larger than the number of negative intracloud flashes. This result indicates that the middle negative charge region was very strong in the whole thunderstorm, the upper positive charge region was slightly stronger than the lower positive charge region, and the lower positive charge region was the weakest. This is consistent with the theoretical inference and
simulation results of other studies regarding the relationship between negative CG flashes and the relative intensities of the middle negative charge and lower positive charge regions (Nag & Rakov, 2009; Mansell et al., 2010; Iudin et al., 2017).

During the early development stage of the two thunderstorm regions or the individual cells, the charge structure of each cell maintained an inverted dipole, and negative CG flashes and negative intracloud flashes mainly dominated the types of lightning flashes, as shown in Tables 1–3. The negative charge region of Region 1 was at a height of 4.5–6 km (AGL), while the negative charge region of Region 2 was at 4–5 km (AGL). The radar echo observations indicated that the 40-dBZ echo zone only reached 8 km (AGL), and the area of the 40-dBZ echo zone was small in the development stage. This indicates that the convection intensity was relatively weak during the initial development stage of the storm cells, resulting in an inverted dipole charge structure.

Multiple cells merged during the intense development of the thunderstorm in its mature phase; in addition, the charge structure transformed into a tripole structure, and the frequencies of negative CG flashes and positive intracloud flashes in Region 1 increased rapidly. The tripole charge structure of Region 1 generated 327 lightning flashes, including 208 negative CG flashes, 74 positive intracloud flashes, and 41 negative intracloud flashes, accounting for 63.6%, 22.6%, and 12.5%, respectively, of the total number of lightning flashes from Region 1 during this stage (Figure 19). The entire charge region was uplifted, with the upper positive charge region reaching a height of 7.5–10 km (AGL) and the middle negative charge region rising to 5–7 km (AGL), maintaining the tripole charge structure for a significant duration. Region 2 generated a

![Figure 17. Schematic diagram of the three types of negative CG flashes: (a) Type I, (b) Type II, and (c–e) Type III.](image)

| Table 1 | Lightning Type and Quantity for Cells 1, 2, 4, and 5 During the Initial Development of Each Thunderstorm Region |
|---------|----------------------------------------------------------------------------------------------------------|
| Lightning type               | Cells 1 and 2 (inverted dipole) | Cells 4 and 5 (inverted dipole) |
|--------------------------------|----------------------------------|-------------------------------|
| Negative intracloud flash    | 9                                | 5                             |
| Positive intracloud flash     | 0                                | 0                             |
| Type 1 negative CG flash      | 32                               | 23                            |
| Type 2 negative CG flash      | 0                                | 0                             |
total number of 203 lightning flashes within its tripole charge structure, including 120 negative CG flashes, 39 positive intracloud flashes, and 44 negative intracloud flashes, accounting for 59.1%, 19.2%, and 21.7%, respectively, of the total number of lightning flashes from Region 2 during this stage (Figure 19). The entire charge region of Region 2 also rose during this stage, with the upper positive charge region reaching a height of 7–9 km (AGL) and the middle negative charge region reaching a height of approximately 6 km (AGL).

As Figures 4b and 11b shown, the heights of 40- and 20-dBZ radar echoes dramatically rose during the cell merging process. This indicated that the updraft was enhanced and the height of upper positive charge region and middle negative charge region were lifted and reached the maximum height. In addition, the thicknesses of the upper positive charge region and negative charge region increased, meaning that the charge intensities of the upper positive charge region and negative charge region also increased. However, upon comparing the charge region development of Regions 1 and 2 in Figures 9 and 14, respectively, we can see that the height of the upper positive charge region of Region 2 was lower than that of Region 1 and that the radiation source of Region 2 was less than that of Region 1, as well as that the discharge region in Region 2 was discontinuous. In comparing the number of different types of lightning flashes in the tripole charge structure, the negative CG flash ratio for Region 1 during this stage was 63.6%, which was slightly larger than that of Region 2 (59.1%), as was the positive intracloud flash ratio, at 22.6% (larger than the 19.2% for Region 2), but the negative intracloud flash ratio was only 12.5% (smaller than the 21.7% observed for Region 2). Upon comparing the development processes of thunderstorm Regions 1 and 2, it is clear that the evolution of thunderstorm Region 1 was more dramatic than that of thunderstorm Region 2, and the intensity of the updraft in Region 1 was stronger than that in Region 2. Therefore, the height and intensity of the same polarity charge region in Region 1 were different from those in Region 2. Thus, due to the strong middle negative charge region and the upper positive charge region being slightly stronger than the lower positive charge region and to their existence for a long time in Region 1, a slightly higher negative CG flash ratio and positive intracloud flash ratio resulted in this region. Due to the strong middle negative charge region and the lower positive charge region being slightly stronger than the upper positive charge region in Region 2, there was a relatively small negative CG flash ratio (59%) but a relatively high negative intracloud flash ratio. Additionally, the above analysis also suggests that because Regions 1 and 2 never completely merged, the partial merger served to strengthen Region 1 while weakening Region 2.

### Table 2

| Lightning type          | Tripole | Inverted dipole | Normal dipole |
|-------------------------|---------|-----------------|---------------|
| Negative intracloud flash | 41      | 10              | 0             |
| Positive intracloud flash | 74      | 0               | 6             |
| Hybrid intracloud flash  | 4       | 0               | 0             |
| Type 1 negative CG flash | 192     | 19              | 0             |
| Type 2 negative CG flash | 5       | 0               | 2             |
| Type 3 negative CG flash | 11      | 0               | 0             |

### Table 3

| Lightning type          | Tripole | Inverted dipole | Normal dipole |
|-------------------------|---------|-----------------|---------------|
| Negative intracloud flash | 44      | 9               | 0             |
| Positive intracloud flash | 39      | 0               | 4             |
| Hybrid intracloud flash  | 0       | 0               | 0             |
| Type 1 negative CG flash | 115     | 38              | 0             |
| Type 2 negative CG flash | 3       | 0               | 0             |
| Type 3 negative CG flash | 2       | 0               | 0             |
As the thunderstorm developed into its dissipation stage, the height of the less than 40-dBZ echo region and the echo top quickly dropped, and the area of the strong echo zone decreased sharply. The height of the charge region also rapidly dropped, with the charge structure changing into an inverted dipole or a normal dipole structure. This accompanied the rapid decrease of the lightning frequency. In particular, the number of negative CG flashes dropped to almost zero. This change is consistent with Williams's theory that the cloud height is very well correlated with the flash rate (Williams 1985). This shift illustrates how the charge region rapidly weakened at this time.

4.2. Statistical Analysis of Single Return Stroke Negative CG Flashes in Different Charge Structures

Data on the return stroke times were used in conjunction with the statistics gathered for the negative CG flashes to evaluate the number of return strokes that occurred for each flash during the storm. The statistical data showed that negative CG flashes with only one return stroke accounted for 60% of all negative CG flashes in the inverted dipole charge structure and 31% of all negative CG flashes in the tripole charge structure. This indicated that the negative CG flashes with only one return stroke occurred at a much higher proportion among all the negative CG flashes in the inverted dipole charge structure than in the tripole charge structure, which means that most of the negative CG flashes that occurred in the tripole charge structure were multiple return strokes. Williams et al. (2016) studied the stroke multiplicity and horizontal scale of negative charge regions in thunderclouds. The results indicated an exceptionally low stroke multiplicity in the initial ground flashes, which was a finding consistent with the limited space available for positive leader extension into new regions of negative charge space in compact cells. Negative CG flashes with only one return stroke made up a large proportion of inverted charge region in this thunderstorm. Furthermore, the inverted charge structure often appeared in the development stage of the cells or the dissipation stage of the thunderstorm, and the tripole charge structure often appeared in the mature stage. We compared the lightning flash location maps in different stages. The horizontal scale of the lightning flashes is in the range of 10 km during the development stage of thunderstorm, and the range of the horizontal scale of the lightning flashes reached 30 km during the mature stage. According to the relationship between the stroke multiplicity and horizontal scale of the negative charge regions, negative CG flashes with only one return stroke accounted for most of the inverted charge structure because of the small horizontal scale of the negative charge regions.

In the mature stage, the updraft was enhanced, and the area of the charge region was enlarged, resulting in an increase in multiple-stroke CG flashes. This is in agreement with the results obtained by Williams et al. (2016).

4.3. The Correlations of the Temperature Layer and Radar Echo With the Charge Structure

In the development process of this thunderstorm, the height of the upper positive charge region ranged from 6 km (AGL) to 10 km (AGL), corresponding to radar echo zone intensities between 20 and 40 dBZ. This height range is associated with the temperature layer between −17.2 and −45 °C. The height of the middle negative charge region ranged between 4 km (AGL) and 7 km (AGL), corresponding to radar echo zone intensities between 30 and 50 dBZ. This height range is associated with the temperature layer between −4.6 and −24 °C. The height of the lower positive charge region ranged between 2 km (AGL) and 4.5 km (AGL), corresponding to radar echo zone intensities between 40 and 60 dBZ. This height range is associated with the temperature layer between 9 and −7 °C. The lightning radiation sources in the weak cell region were distributed mainly in the echo region with intensities below 40 dBZ.
According to the noninductive electrification mechanism (Takahashi, 1978), if −10 °C is the reversal temperature, the temperature of the upper positive charge region will be less than −17.2 °C, which exceeds the reversal temperature. The upper positive charge region corresponding to a small radar echo intensity range may mainly include small positively charged hydrometeors, such as ice crystals. The middle negative charge region was distributed mainly between −4.6 and −17.2 °C and contained the region just above and below the reversal temperature, which corresponds to the mixed-phase region and is associated with the moderate radar echo intensity range; hence, the middle negative charge region may have included large negatively charged graupel particles and small negatively charged ice crystal particles. The lower positive charge region was located mainly below the temperature layer of −4.6 °C (the freezing temperature layer was located at 3.2 km (AGL)), and part of the lower positive charge region already extended into the warm cloud region. Therefore, the lower positive charge region corresponds to a large radar echo intensity range, which mainly includes large positively charged hydrometeors such as graupel particles and falling positively charged hydrometeors. The middle negative charge region corresponds to a larger range of temperatures, and hydrometeors are the most abundant. The upper and lower positive charge regions contain mainly small particles and large particles, respectively. Therefore, this formation structure may be the reason why the middle negative charge area was the most powerful and the upper and lower positive charge regions were relatively weak.

In addition to the above analysis, a comparison of the radar echo intensities and charge structures in Regions 1 and 2 reveals that the appearance of the upper positive charge region is closely related to an updraft. When the area of the 40-dBZ echo region expands and the height of the 20-dBZ echo region rises, the updraft strengthens, and the upper positive charge region appears. At the same time, the heights and thicknesses of all charge regions increase. Furthermore, the horizontal scale of the charge region also becomes enlarged. At this time, the lightning frequency increases, especially the frequency of positive intracloud lightning flashes, which rapidly become more frequent. However, when the height of the 20-dBZ echo region decreases, the 40-dBZ echo region descends to 7 km (AGL), at which point the lower positive charge region corresponds to an enlarged echo intensity range, the updraft weakens, and the area of the upper positive charge region is reduced. At this time, the positive intracloud flash frequency decreases, and the negative intracloud flash frequency increases, meaning that the upper positive charge region weakens and the lower positive charge region strengthens, while the negative CG flash frequency is far greater than the intracloud flash frequency. According to the analysis of radar echo, charge region, and lightning frequency changes, the increase of the radar echo height means that the updraft is enhanced and the upper positive charge region appears. At this time, the spatial region involved in lightning discharge is expanded, the horizontal scale of the negative charge region also expands, and the lower positive charge region is small, causing frequency changes of positive intracloud flashes and negative CG. However, when the radar echo shows a decrease in height, this means that the updraft in the thunderstorm becomes weak. The upper positive charge region participating in lightning discharge weakens, and the lower positive charge region participating in lightning discharge strengthens. At this time, the discharge mainly occurs between the lower positive charge region and middle negative charge region, producing more negative CG flashes and negative intracloud flashes. In addition, the height of the center of the negative charge is relatively low above the ground in the Qinghai-Tibet Plateau, while the horizontal scale of the negative charge region is relatively large. Therefore, under the induction of the weak lower positive charge region, the negative leader can more easily reach the ground than in low-altitude regions.

5. Conclusion and Discussion

In this study, lightning VHF radiation source location data and synchronous fast antenna and radar echo data were used to analyze the correlation between the charge structure evolution and corresponding lightning type and frequency during the merging and splitting of a negative CG flash predominated multicell thunderstorm. The following conclusions were obtained:

1. In the initial development process of each thunderstorm region, the charge structure of each cell generally presented as an inverted dipole, and the height of the charge region was relatively low. Lightning flashes were dominated mainly by negative CG flashes and a small number of negative intracloud flashes. During the strengthening and maturation stage of the thunderstorm, the merging of multiple
cells enhanced the thunderstorm, and the charge structure changed from an inverted dipole structure to a tripole structure. The charge region height rose, and the lightning flashes were still dominated by negative CG flashes. When each thunderstorm region eventually split and declined in strength, the charge structure shifted to an inverted dipole structure or a normal dipole structure. Finally, the height of the charge region gradually descended as the lightning frequency rapidly decreased.

2. As the strong echo zone of the thunderstorm region developed, the distribution of the charge region became uneven and asymmetrical, making the charge structure near the center of the strong echo appear to be a positive dipole structure, but the charge structure presented as a negative dipole structure far from the strong echo zone. However, the negative charge region was essentially at the same height in both areas, so the thunderstorm charge structure remained a tripole structure.

3. In the inverted dipole charge structure, negative CG flashes accounted for 77.2% of the total number of lightning flashes. In the tripole charge structure, negative CG flashes, positive intracloud flashes, and negative intracloud flashes accounted for 62%, 21%, and 16%, respectively, of all lightning flashes. Over the full span of the thunderstorm, the number of negative CG flashes was far greater than the number of intracloud flashes, and the number of positive intracloud flashes was larger than the number of negative intracloud flashes. This result indicates that this thunderstorm is unique in that the number of negative CG flashes was far greater than the number of intracloud flashes. In this special thunderstorm, the middle negative charge region was the strongest layer of the whole event, the upper positive charge region was slightly stronger than the lower positive charge region, and the lower positive charge region was the weakest.

4. Multiple cells merged to form Regions 1 and 2 in the thunderstorm, with Region 1 being stronger than Region 2. In the tripole charge structure that both regions developed, the proportions relating negative intracloud flashes, positive intracloud flashes, and negative CG flashes were 0.13:0.23:0.64 in Region 1 and 0.19:0.22:0.59 in Region 2. These results indicate that the middle negative charge region of both Regions 1 and 2 was the strongest; however, the upper positive charge region was stronger than the lower negative charge region in Region 1, and the upper positive charge region was weaker than the lower positive charge region in Region 2. This result illustrates that the relative intensity of the charge region directly determined the lightning quantity and its frequency.

5. An analysis of the statistical data gathered on negative CG return stroke times showed that the ratio of single return stroke negative CG flashes to the total number of negative CG flashes was 0.6 in the inverted dipole charge structure but only 0.31 in the tripole charge structure during the evolution of the thunderstorm. This indicates that the convection of the thunderstorm was weak during the development stage and that the horizontal scale of the negative charge region was small; therefore, negative CG flashes mainly occurred with a single return stroke CG in this stage. When the convection of the thunderstorm was enhanced during the mature stage of the thunderstorm and the intensity and scale of the middle negative charge region were also enhanced, this resulted in an increase in multiple-stroke CG flashes.

6. According to the comparative analysis of radar echo intensities and charge structures in thunderstorm Regions 1 and 2, the updraft was strengthened, causing the area of the >40-dBZ vertical echo region to expand and the height of the 20-dBZ echo region to rise. At this time, the upper positive charge region appeared, and the heights of all charge regions increased. Additionally, the lightning frequency increased, especially the frequency of positive intracloud lightning flashes, which rapidly became more frequent. However, when the height of the 20-dBZ echo region decreased and the area of the >40-dBZ echo region descended, the updraft became weak, the positive intracloud flash frequency decreased, the negative intracloud flash frequency increased, the upper positive charge region weakened, and the lower positive charge region strengthened. Nevertheless, the number of negative CG flashes still far exceeded the number of intracloud flashes.

In the past, researchers generally believed that the lower positive charge region helps to enhance the electric field at the bottom of the main negative charge region and thereby facilitate the launching of a negatively charged leader toward the ground. On the other hand, the presence of an excessive lower positive charge region may prevent the occurrence of negative CG discharges by “blocking” the progression of a descending negative leader from reaching the ground and thus “converting” the potential CG flash into an intracloud flash. This theory was studied by qualitative analysis and model simulation (Nag & Rakov., 2009; Mansell et al., 2010; Iudin et al., 2017). The results in this paper indicate that 63.3% of all the lightning flashes
produced by the investigated thunderstorm were negative CG flashes, indicating that the negative charge region was very strong and large and that the lower positive charge region was weak in both the inverted dipole charge structure and the tripole charge structure. The negative CG flash ratio for Region 1 was 63.6%, slightly higher than that for Region 2 (59.1%), and the negative intracloud flash ratio of 12.5% for Region 1 was relatively low (i.e., lower than that of 21.7% for Region 2). These results regarding the evolution processes of the charge structures in Regions 1 and 2 show that the lower positive charge region in Region 1 was weaker than that in Region 2. This helps to demonstrate that the intensity of the lower positive charge region relative to the middle negative charge region directly affects the proportions of negative CG and negative intracloud flashes.

In the thunderstorm process studied in this paper, when negative CG flashes were the most numerous and the charge structure was a tripole charge structure, the height of the thunderstorm was at its maximum (the upper positive charge region reached a height of 7–10 km (AGL)) and its spatial extent was the greatest. The changes of the radar echo height with time show that the echo value reached the maximum height in this stage and that the updraft was in its strongest stage. The 3-D lightning location radiation source map also shows (Figures 9 and 14) that the space region participating in lightning discharge also reached the maximum in this stage, and the horizontal extension range of the negative charge region expanded. The analysis of the lightning discharge process in this stage shows that the middle negative charge region always continuously discharged into the upper or to the ground until the time when hardly any lightning flashes occurred between the upper positive charge region and the middle negative charge region, the negative intracloud flash increased, and the negative CG flash frequency reached its peak. These characteristics mean that when the upper positive charge region is very strong, the middle negative charge region mainly discharges with the upper positive charge region and produces positive intracloud flashes. After a long time, when the upper positive charge region no longer produces lightning flashes with the negative charge region, the negative charge region will produce more negative intracloud flashes with the lower positive charge region. At the same time, a large number of negative CG will be produced, reaching a peak under the induction of the lower positive charge region. This shows that a strong updraft can cause a strong upper positive charge region, which is stronger than the lower positive charge region, to appear in a thunderstorm, and it becomes easier to form a stronger electric field with the middle negative charge region to produce more positive intracloud flashes. However, the updraft cannot maintain the upper positive charge region for a long time in the Qinghai-Tibet Plateau. Obviously, the updraft can make the middle negative charge region and the lower positive charge region exist for a long time. We also observed the negative CG discharge process in this thunderstorm. The negative CG has a long intracloud discharge process before the negative leader reaches the ground during the development stage of the cells. During the mature stage, the negative leader of the negative CG flash quickly directly develops to the ground. This illustrates that the magnitude of the negative charge region is much larger than the magnitude of the lower positive charge region in the mature stage. On the other hand, the radiation source distribution shows that the horizontal distribution diameter of the negative charge region reaches more than 30 km and that the height of negative charge center is relatively low (only 4 km) to the ground in the plateau. This is favorable for the occurrence of negative CG in the large horizontal scale of the negative charge region (Williams et al., 2016). Therefore, the strong negative charge region, weak positive charge region, and short distance from the central negative charge to the ground make the negative leader reach the ground easily to produce a large number of negative CG flashes.

The tripole charge structure of a “normal” thundercloud has three charge centers: the main positive center in the upper layer, the main negative center in the middle layer, and an additional positive center below the main negative center (Williams, 1989). The magnitudes of the main positive and negative charges are typically some tens of coulombs, while the lower positive charge is likely 10C or less. From this paper and the observation results for thunderstorms on the Qinghai-Tibet Plateau obtained using 3-D lightning VHF radiation source location systems in previous studies (Li et al., 2013, 2017), it was determined that the cell charge structures of isolated cell or multicell thunderstorms maintain inverted charge structure for a long duration during their development stage. With the development of the thunderstorm, the charge structure becomes tripole. During this period, a large number of discharges are produced between the upper positive charge region and the middle negative charge region. After a period of time, the lightning discharge starts to mainly occur between the middle negative charge region and the lower positive charge region, generating more lightning flashes. Thus, the tripole charge structure of the plateau is derived from the inverted charge
structure. The appearance of the upper positive charge region is not continuous, while the lower positive charge region exists almost throughout the whole thunderstorm evolution process and discharges with the middle negative charge region. Therefore, the tripole charge structure in the Qinghai-Tibet Plateau is different from that of normal thunderstorm. Wang et al. (2019) used numerical modeling to simulate the formation of a large lower positive charge center (LPCC) in a Qinghai-Tibet Plateau thunderstorm. The results showed that the unique environmental conditions of the Qinghai-Tibet Plateau, which include weak convection and a low freezing level, are fundamental to the formation of a large LPCC. Other research on the typical features of stratification on the plateau found that the entire layer is mostly weak and unstable, causing convective activity to be frequent, but its strength is small, and its time of duration is short (Zhang et al., 2005). This is totally different from the case for plain thunderstorms. According to the height changes of radar echoes, when the updraft is strengthened, a strong upper positive charge is generated. At this time, the charge structure in the thunderstorm is similar to the normal tripole, but the lower positive charge region is stronger than that in the normal tripole. However, the updraft in the plateau as a whole is weak, and it cannot provide the positively charged particles needed for the upper positive charge region over a long time. Therefore, the positive intracloud flash frequency decreases sharply when the updraft weakens, and then the lightning discharge mainly occurs between the middle negative charge region and the lower positive charge region, generating more negative intracloud flashes and negative CG flashes in this thunderstorm, the convection in Region 2 was weaker than that in Region 1, so the lightning flashes that occurred between the lower positive charge region and the middle negative charge region in Region 2 were greater in number than those in Region 1. Based on the above analysis, the overall weak convection in the thunderstorm may have been the main cause of the tripole charge structure in this area being different from the normal tripole charge structure.

In addition, the 0 °C layer during this thunderstorm was located at 3.2 km (AGL), and the CBH was 1.4 km (AGL). The 0 °C layers of other thunderstorms in this region are generally located at an altitude of 2 km (AGL), and the CBH is around 1 km. The height of the 0 °C layer of this thunderstorm was higher than those of other thunderstorms in this region. This means that the warm cloud region in this thunderstorm was thicker than those in other thunderstorms. The lower positive charge region was located between 2 km (AGL) and 4 km (AGL), corresponding to a temperature layer between 9 and −4.6 °C. The lower positive charge region corresponding to the thickness of the above-freezing temperature layer is thin, and most of the lower positive charge region is in the warm cloud region. The warm cloud region is composed of few positively charged hydrometeors, which may have caused the intensity of the lower charge region to be relatively weak relative to those of other thunderstorms in this region. The middle negative charge region was located between 4 km (AGL) and 6 km (AGL), corresponding to a temperature layer between −4.6 and −17.2 °C. The middle negative charge region was located between 3.5 km (AGL) and 5 km (AGL) in the other thunderstorms, corresponding to a temperature layer between −6.5 and −15 °C (Li et al., 2017). As a result, the thickness and temperature range of the middle negative charge region was larger than those of other thunderstorms in this region. Therefore, the middle negative charge region of this thunderstorm was stronger than that of other thunderstorms in this region. As described above, the charge region distribution included a relatively strong middle negative charge region and a relatively weak lower positive charge region compared to those of other thunderstorms in this region. Such a distribution of the charge region is conducive to the occurrence of negative CG flashes. Therefore, this thunderstorm process also showed some different characteristics of lightning activity compared to those of other thunderstorms.

In winter thunderstorms of Japan, some cells exhibit main positively charged regions below the middle main negatively charged region at a lower level that is warmer than approximately −10 °C. Zheng et al. (2019) used 3-D Lightning Mapping Array flash source data, radar echo data, and sounding data to investigate three winter thunderstorms in Japan. The cells with lower main positively charged regions featured weaker convection, as indicated by low radar echoes, and therefore, the main charging process occurred at or below the −10 °C level, in a region where graupel gains a positive charge by riming electrification (Takahashi, 1978). This is similar to the weak convection in summer thunderstorms on the Qinghai-Tibet Plateau; that is, the weak convection on the plateau may also be the cause of more lightning discharges occurring between the middle negative charge region and the lower positive charge region. Upon comparing the radar echo of winter thunderstorm in Japan and thunderstorm Qinghai-Tibet Plateau, the echo value of 20
Acknowledgments

This work complies with the AGU data policy, and the data used in this paper can be obtained from http://doi.org/10.5281/zenodo.3456788 or the authors. This work was supported by the Major Research Plan of the National Natural Science Foundation of China (Grant 10.5281/zenodo.3456788). We are indebted to all those who participated in our lightning observation experiments in Qinghai. We also thank the Qinghai Provincial Meteorological Bureau for their support. The authors would like to thank Dr. Earle Williams and other reviewers for their valuable comments.

References

Bruning, E. C., Weiss, S. A., & Calhoun, K. M. (2014). Continuous variability in thunderstorm primary electrification and an evaluation of inverted-polarity terminology. Atmospheric Research, 135-136, 274–284.

Huang, X. Y., Wang, X. P., Wang, J. S., Feng, J. Y., Wang, S. J., & Chen, F. (2017). Spatio-temporal changes of 0 °C isotherm height in China during summer half year of 1970—2012. Meteorological monthly, 43(3), 286–293.

Judd, D. I., Rakov, V. A., Mareev, E. A., Judin, F. D., Syssoev, A. A., & Davydenco, S. S. (2017). Advanced numerical model of lightning development: Application to studying the role of LPCR in determining lightning type. Journal of Geophysical Research: Atmospheres, 122, 6416–6430. https://doi.org/10.1002/2016JD026261

Jacobson, E. A., & Kider, E. P. (1976). Electrostatic field changes produced by Florida lightning. Journal of the Atmospheric Sciences, 33(1), 103–117.

Kasemir, H. W. (1960). A contribution to the electrostatic theory of lightning discharge. Journal of Geophysical Research, 65, 1873–1878.

Krehbiel, P. R., Thomas, R. J., Rison, W., Hamlin, T., Hamlin, J., & Davis, M. (2000). GPS-based mapping system reveals lightning inside storms. Eos, Transactions of the American Geophysical Union, 81(3), 21–25.

Li, Y. J., Zhang, G. S., Wang, Y. H., & Wu, B. (2017). Observation and analysis of electrical structure change and diversity in thunderstorms on the Qinghai-Tibet Plateau. Atmospheric Research, 194, 130–141. https://doi.org/10.1016/j.atmosres.2017.04.031

Li, Y. J., Zhang, G. S., Wen, J., Wang, D. H., Wang, Y. H., Zhang, T., et al. (2013). Electrical structure of a Qinghai–Tibet Plateau thunderstorm based on three-dimensional lightning mapping. Atmospheric Research, 134, 137–149.

Liu, X., Guo, C., Wang, C., & Yan, M. (1987). The surface electrostatic field change produced by lightning flashes and the positive charge layer of the thunderstorm (in Chinese). Acta Meteorologica Sinica, 45, 500–504.

Liu, X. S., Ye, Z. X., Shao, X. M., Wang, C. W., Yan, M. H., & Guo, C. M. (1989). Intraccloud lightning discharges in the lower part of thundercloud. Acta Meteorologica Sinica, 3(2), 212–219.

MacGorman, D. R., Rust, W. D., Schuur, T. J., Biggerstaff, M. I., Straka, J. M., Ziegler, C. L., et al. (2008). TELEX: The Thunderstorm Electrification and Lightning Experiment. Bulletin of the American Meteorological Society, 69, 997–1013.

Mansell, E. R., Ziegler, C. L., & Bruning, E. C. (2010). Simulated electrification of a small thunderstorm with two-moment bulk microphysics. Journal of the Atmospheric Sciences, 67(1), 171–194. https://doi.org/10.1175/2009JAS2965.1

Mazur, V., & Ruhnke, L. H. (1993). Common physical processes in natural and artificially triggered lightning. Journal of Geophysical Research, 98, 12913–12930.

Nag, A., & Rakov, V. A. (2009). Some inferences on the role of lower positive charge region in facilitating different types of lightning. Geophysical Research Letters, 36, L05815. https://doi.org/10.1029/2009GL036783

Qie, X., Zhang, T., Chen, C., Zhang, Z., Zhang, T., & Wei, W. (2005). The lower positive charge center and its effect on lightning discharges on the Tibetan Plateau. Geophysical Research Letters, 32, L05814. https://doi.org/10.1029/2004GL022152

Qie, X. S., Zhang, T. L., Zhang, G. S., Zhang, T., & Kong, X. Z. (2009). Electrical characteristics of thunderstorms in different plateau regions of China. Atmospheric Research, 91, 244–249.

Rison, W., Thomas, R. J., Krehbiel, P. R., Hamlin, T., & Harlin, J. (1999). A GPS-based three-dimensional lightning mapping system: Initial observations in central New Mexico. Geophysical Research Letters, 26, 3573–3576.

Rust, W. D., MacGorman, D. R., Bruning, E. C., Weiss, S. A., Krehbiel, P. R., & Thomas, R. J. (2005). Inverted-polarity electrical structures in thunderstorms in the Severe Thunderstorm Electrification and Precipitation Study (STEPS). Atmospheric Research, 76, 247–271. https://doi.org/10.1016/j.atmosres.2004.11.029

Shao, X. M., & Krehbiel, P. R. (1996). The spatial and temporal development of intraccloud lightning. Geophysical Research Letters, 101, 26641–26668.

Shao, X. M., & Liu, X. S. (1987). A preliminary analysis of intraccloud lightning flashes and lower positive charge of thunderclouds. Plateau Meteorology, 6, 317–325.

Takahashi, T. (1978). Rimming electrification as a charge generation mechanism in thunderstorms. Journal of the Atmospheric Sciences, 35, 1536–1548.

Thomas, R., Krehbiel, P., Rison, W., Hunyady, S., Winn, W., Hamlin, T., & Hamlin, J. (2004). Accuracy of the lightning mapping array. Geophysical Research Letters, 109, D14207. https://doi.org/10.1029/2004JD004549
dBZ for winter thunderstorms is generally distributed below 6 km (AGL), with the highest reaching 8 km, while the echo value of 40 dBZ is mainly distributed at 4 km (AGL), with the highest at 5 km (AGL). However, during the thunderstorm process in summer on the Qinghai-Tibet Plateau, the echo value of 20 dBZ is mainly distributed at 10–12 km (AGL) and that of 40 dBZ is mainly distributed at 5–8 km (AGL), with a maximum of 10 km (AGL). The above data indicate that the convection of summer thunderstorms on the Qinghai-Tibet Plateau is weaker than that in other areas, but it is still stronger than that in winter thunderstorms. Therefore, the charge regions of summer thunderstorms in the plateau can reach a height of 10.5 km (AGL), while the charge regions of winter thunderstorms in Japan are mainly distributed at 0.7–5.7 km (AGL).
Wang, D., Liu, X., & Wang, C. (1990). A preliminary analysis of the characteristics of ground discharges in thunderstorms near Zhongchuan, Gansu province. *Plateau Meteorology*, 9(4), 405–410.

Wang, F., Deng, X. H., Zhang, Y. J., Li, Y. J., Zhang, G. S., Xu, L. T., & Zheng, D. (2019). Numerical simulation of the formation of a large lower positive charge center in a Tibetan Plateau thunderstorm. *Journal of Geophysical Research: Atmospheres*, 124(16), 9561–9593. https://doi.org/10.1029/2018JD029676

Wiens, K. C., Rutledge, S. A., & Tessendorf, S. A. (2005). The 29 June 2000 supercell observed during STEPS. Part II: Lightning and charge structure. *American Meteorological Society*, 62, 4151–4177.

Williams, E., Mushtak, V., Goodman, S., & Boccippio, D. (2005). Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmospheric Research*, 76(1–4), 288–306.

Williams, E. R. (1989). Large-scale charge separation in thunderclouds. *Journal of Geophysical Research*, 90, 6013–6025.

Williams, E. R., Mattos, E. V., & Machado, L. A. T. (2016). Stroke multiplicity and horizontal scale of negative charge regions in thunderclouds. *Geophysical Research Letters*, 43, 5460–5466. https://doi.org/10.1002/2016GL068924

Wu, B., Zhang, G., Wen, J., Zhang, T., Li, Y., & Wang, Y. (2016). Correlation analysis between initial preliminary breakdown process, the characteristic of radiation pulse, and the charge structure on the Qinghai-Tibetan Plateau. *Journal of Geophysical Research: Atmospheres*, 121, 12434–12459. https://doi.org/10.1002/2016JD025281

Zhang, C. H., Yan, M. H., Dong, W. S., & Zhang, Y. J. (2005). Analyses on atmospheric stratification characteristics of thunderstorms over Qinghai-Xizang Plateau (in Chinese). *Plateau Meteorology*, 24(5), 741–747.

Zhang, G. S., Li, Y. J., Wang, Y. H., Zhang, T., Wu, B., & Liu, Y. X. (2015). Experimental study on location accuracy of a 3D VHF lightning-radiation-source locating network. *Science China: Earth Sciences*, 58, 2034–2048. https://doi.org/10.1007/s11430-015-5119-1

Zhang, G. S., Wang, Y. H., Qie, X. S., Zhang, T., Zhao, Y. X., Li, Y. J., & Cao, D. J. (2010). Using lightning locating system based on time-of-arrival technique to study three-dimensional lightning discharge processes. *Science China: Earth Sciences*, 53, 591–602.

Zhang, Y. J., Dong, W. S., Zhao, Y., Zhang, G. S., Zhang, H. F., Chen, C. P., & Zhang, T. (2004). Study of charge structure and radiation characteristic of intracloud discharge in thunderstorms of Qinghai-Tibet Plateau. *Science China: Earth Sciences*, 47(2), 108–114.

Zheng, D., Wang, D., Zhang, Y., Wu, T., & Takagi, N. (2019). Charge regions indicated by LMA lightning flashes in Hokuriku's winter thunderstorms. *Journal of Geophysical Research: Atmospheres*, 124, 7179–7204. https://doi.org/10.1029/2018JD030060

Zhou, Y. J., Qie, X. S., & Xie, Y. R. (2004). Characteristics of lightning physics in the center of Qinghai-Tibet Plateau. *Proceedings of the CSEE*, 24(9), 198–203.