Electrical structure of a Qinghai–Tibet Plateau thunderstorm based on three-dimensional lightning mapping

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1. Introduction

Summer thunderstorms have been reported from early days of atmospheric electricity research usually exhibiting dominant negative electric field at the ground (Simpson and Scrase, 1937; Simpson and Robinson, 1941). However, many thunderstorms that occurred in Chinese inland plateau have been observed as exhibiting dominant positive electric field (e.g., Liu et al., 1987; Wang et al., 1990; Qie et al., 1998; Zhang et al., 2004; Wang et al., 2007). The polarity of the electric field in the study is defined according to the ‘atmospheric electricity’ sign convention. Namely that a ‘positive’ electric field is downward-directed that corresponds to positive charge overhead. In order to understand what thunderstorm charge structures produced in such dominant positive electric field, various experimental observations have been carried out in China since the 1980s (Shao and Liu, 1987; Liu et al., 1987; Qie et al., 1998, 2005a, 2005b, 2009; Zhao et al., 2010). Most of these studies suggest that a tripole charge structure but with a larger-than-usual lower positive charge center (LPCC) at the base of some thunderclouds is the reason of the dominant positive electric field. However, one should note that most of the previous observations were restricted by measurement and analysis techniques, and thus the qualitatively deduced results are not adequate in understanding spatially and temporally the evolution of the electric structure of an entire thunderstorm. Recently, 3D lightning mapping techniques have made possible to track the charge structure evolution more accurately for an...
entire thunderstorm. In this study, in order to better understand the charge structure of thunderstorms in Qinghai-Tibetan Plateau, we have employed two 3D lightning mapping systems, one based on a broadband electric field antenna location system (Li et al., 2012) and another on a very high frequency (VHF) radiation source locating system (Zhang et al., 2010; Wang et al., 2012). The VHF systems are similar to the lightning mapping array (LMA) system now used worldwide by many authors (e.g., Krehbiel et al., 2000; Rison et al., 1999; Hamlin, 2004; Goodman et al., 2013), which located lightning radiation sources by time of arrival technique with GPS system. With the two 3D mapping systems, we have conducted comprehensive observations on natural lightning discharges at the northeastern verge of the Qinghai-Tibet Plateau since the summers of 2009 (Zhang et al., 2010). This paper is to report our observation results of an isolated thunderstorm that produced dominant positive electric field on the ground.

2. Data and methodology

2.1. Instrumentation and observation

From July to August 2009, a comprehensive observation was conducted in Datong, Qinghai province, China. Datong lies on the northeastern verge of the Qinghai-Tibet Plateau. Datong's climate can be classified as a continental plateau climate. Because the terrain and climate are complex, the storms usually occur in summer, with some even accompanied by destructive hails. For the observation, we have set up seven stations distributed at an area about 15 km in diameter (Fig. 1), where Mingde is the central station (altitude 2496.24 m) and the six affiliated stations were set up in a radial pattern. Each station was equipped with the sensors of the 3D lightning VHF radiation source locating system, the 3D broadband electric field mapping system, a field mill, a fast E-field change antenna and a slow E-field change antenna. The 3D lightning VHF radiation source locating system was operated at its center frequency of 270 MHz with 3 dB bandwidth of 6 MHz (Zhang et al., 2010). The 3D broadband electric field signal received was processed using a digital filter, the resultant bandwidth is from 1.5 kHz to 10 MHz, and the decay time constant is 100 μs (Li et al., 2009). The two systems synchronously receive the radiation pulse signals produced by lightning discharges and then measure the arrival times of impulsive radiation events of lightning at each remote location by taking advantage of GPS technology. The arrival times are determined using a 20 MHz digitizer accurately synchronized by the 1 pulse per second (1PPS) output of a GPS receiver (Motorola M12T) at each station. The systems deal with one peak value event in successive 50 μs time windows with the maximum number

Fig. 1. Map of the observation sites.
up to 20 thousand radiation sources in 1 s. Actual amounts of located radiation points may change according to the number of identified independent pulses from each station. The location error has been estimated by Zhang et al. (2010). Within an observation range of 100 km, the typical horizontal error is about 100 m over the network plane, and the altitude error is less than 300 m, both increasing with the observation range. The fast antenna (with bandwidth 160 Hz–5 MHz, time constant 1 ms and measuring range ±2 kV/m) and the slow antenna (with bandwidth 0.03 Hz–2 MHz, time constant 6 s and measuring range ±8 kV/m and ±16 kV/m) were used to measure the electric field changes of lightning discharge with a time resolution of 0.1 μs. These signals were recorded by computers through A/D converters and were synchronized by a triggering signal from the fast antenna. The time was recorded with a 20 MHz high precision clock synchronized by GPS (1PPS). The field mill (measuring range is ±50 kV/m) was used to measure the electric field on the ground at a sampling rate of 0.1 s. At the central station, a VHF narrowband interferometer (Zhang et al., 2008) and a high-speed camera (FASTCAM 1000 k-c2, 10,000 fps) were also equipped. All the seven stations were connected through wireless broadband communication system. Data collection can be controlled by a triggering signal sent either manually or automatically from the central station. In addition, the radar echo information from a C-band (5 cm) new generation Doppler weather radar (CINRAD/CC) 48 km away from our central station is available for the present study. During the whole observation period, the radar collected conventional data of volume scans every 5–6 min.

2.2. Method of charge structure estimation

This paper uses the 3D VHF location lightning discharge radiation sources to infer the thunderstorm charge structures as done by Hamlin (2004), Thomas et al. (2001), Wiens et al. (2005), Rust and MacGorman (2005), MacGorman et al. (2008) and Bruning et al. (2012) with a lightning mapping array system (Rison et al., 1999; Edens et al., 2012). The method is based on the bidirectional leader model proposed by Kasemir (1960). As described by Mazur and Ruhnke (1993) once a lightning discharge initiates in the strong electric field between regions of net positive and negative charges, it will propagate in opposite directions from the discharge origin and produce negative breakdown and positive breakdown, respectively, at its two front sides. As described by Mazur and Ruhnke (1993), positive charge region is generally penetrated by the negative breakdown, and negative charge region is penetrated by the positive breakdown. Since the negative breakdown is inherently noisier than the positive breakdown at the radio frequencies, frequent and continuous radiations will be received from positive charge region, and dispersive and discontinuous weaker radiations from negative charge region (Shao and Krehbiel, 1996). By studying the direction and the sequence of channel development and the density of mapped points along an apparent channel, as described by Shao and Krehbiel (1996), one can infer which channels propagated in regions of positive charge and which in regions of negative charge. Zhang et al. (2010) have discussed 3D-channel evolutions of typical negative cloud-to-ground (CG), positive CG, intracloud (IC) lightning flashes using the 3D VHF location lightning discharge radiation sources along with the fast and slow electric field changes caused by the lightning discharge. Their results indicated that the method of estimating the charge region from the number of located sources, the propagation direction of the initial breakdown and the time sequence of lightning discharge VHF sources is feasible. In the present study, for each lightning discharge we obtained its 3D radiation source locations, we have analyzed in detail the progression direction, the sequence and the density of all the radiation sources. If a region contains frequent and continuous radiations, we inferred it to be a positive charge region. If a region contains dispersive and discontinuous weaker radiation, we infer it to be a negative charge region. By accumulating the radiation sources for successive lightning discharge over a given time interval, we obtained the predominant charge structure of the thunderstorm.

3. Data analyses and results

3.1. Evolution of thunderstorm and surface electric field

The isolated thunderstorm in this study named thunderstorm 1, occurred over the southern part of the observation network on 6 August 2009 as shown by the radar echo in Fig. 2. It moved eastward from Jile site and finally dissipated at the east side of Liangjiao site. A strong radar echo region (≥40 dBZ) passed over Jile, Xiegou and Liangjiao sites. In the storm developing stage beginning at 08:59 UTC when the storm was west of Jile site as shown in Fig. 2, the maximum intensity of radar echo was less than 35 dBZ. By 09:05 UTC, the storm had reached 40 dBZ at Jile site and its lightning flash rate had increased from 0 to 3 per 5 min. At 09:20 UTC, thunderstorm 1 had entered its mature stage, and its strong echo center was over Xiegou site with the maximum intensity of 53 dBZ, and continued to move on toward Liangjiao. After 09:35 UTC, thunderstorm 1 started to dissipate. During this time, a second thunderstorm, named thunderstorm 2 (09:38 UTC in Fig. 2), developed 20 km away from the center station. Thunderstorm 1 merged with thunderstorm 2 at 09:43 UTC. Around this time, the maximum radar echo intensity of thunderstorm 1 was less than 40 dBZ, while the radar intensity of thunderstorm 2 was over 52 dBZ. At 09:54, thunderstorm 2 began to dissipate. After 09:58 UTC, lightning discharge activities had almost disappeared.

Fig. 3 shows the evolution of the corresponding electric field observed at the ground at Xiegou and Liangjiao sites for the three successive stages described above. At both sites, the dominant electric field is positive. The first lightning discharge occurred at 09:08 when the center of the strong radar echo is located on Jile site. From 09:08 UTC to 09:25 UTC, all the lightning discharges produced negative electric field changes in Xiegou site. After 09:26, some of the discharges produced negative electric field changes and some caused positive electric field changes, and the polarity of the electric field was positive in Xiegou. The thunderstorm 1 was over the Liangjiao at 09:36 when the electric field was negative. Then the thunderstorm began to leave Liangjiao gradually. After 09:48 the thunderstorm has left the station, and the electric field polarity changed from negative to positive.
Fig. 2. Sequence of 2.5 km constant altitude sections of equivalent radar reflectivity factor $Z$ measured by a CINRAD/CC Doppler weather radar. Distances are relative to our center station.

Fig. 3. The evolution of the electric field (not corrected to surface) observed at Xiegou and Liangjiao sites on August 6, 2009.
3.2. Three-dimensional locations of lightning discharge radiation sources

Fig. 4 shows the 3D distribution of radiation sources produced in the initial developing stage (09:08–09:20 UTC) of thunderstorm 1. More than 8900 radiation sources were produced over a period of 12 min. Most of the radiations occurred at a height ranging from 1.5 km to 4 km above the ground. Fig. 5 shows the mapping of an intracloud lightning discharge that occurred at 09:17:34.249 UTC in the developing stage of the thunderstorm. The changes of color from blue, green, yellow to red in the figure indicate the variations of VHF radiation events with time. The discharge lasted 180 ms and had a bi-level structure, located at 2–3 km and 4 km, respectively. The discharge initiation point is located about 4 km above the ground and is denoted as “*” in Fig. 4. The discharge first propagated vertically downward to a region at a height of 3 km, and then developed horizontally extending to the east and then more than 7 km to the north with the channel height gradually descending. After 70 ms, a few radiation events occurred in the region at a height of 4 km between 09:17:34.319 and 09:17:34.328, and are circled by an ellipse in Fig. 4. Meanwhile, radiations continued in the lower region for about 40 ms and then stopped at the height of 2 km. Thereafter, the radiation events increased at the height of 4 km. A subsequent breakdown extended horizontally along the upper level channel near the lightning starting point. From the direction, the sequence of the channel development and the density of the radiation source points, the high level region (around 4 km high and being marked with a symbol ‘–’) is inferred to be a negative charge region and the low level region (around 1.5 km high) is a positive charge region. Therefore the intracloud discharge is a polarity inverted discharge. During the initial developing stage a total of 17

![Fig. 4. Distribution of radiation sources during 09:08–09:20 UTC. (a1) The expanded view of Xiegou field mill data. (a2) Height–time plot panel, (b) north-southward vertical projection, (c) height distribution of number of radiation events, (d) plan view, (e) east-westward vertical projection of lightning radiation sources. “x” indicates the occurrence timing of positive CG lightning.](image-url)
lightning discharges occurred with 16 of them being IC discharges and 1 positive CG discharge. All the 17 lightning discharges reduced the dominant positive electric field at the ground. 14 of the 16 IC discharges exhibited similar bi-level structures as shown in Fig. 5. The remaining 2 can’t be judged because of insufficient number of located sources. The only CG discharge occurred just after the beginning of the developing stage and was marked with a symbol “x” in Fig. 4. The CG discharge started with an intra-cloud discharge process lasting about 65 ms that also exhibited a bi-level structure as the IC discharges. From all these observed facts, we inferred that during the initial developing stage a positive charge region with a horizontal extent of roughly 10 km existed at a height ranging from 1 km to 3 km and a negative charge region existed at a height of 4 km.

Fig. 5. An intracloud flash occurring at 09:17:34 UTC on August 6, 2009. (a) Height–time plot panel, (b) north-southward vertical projection, (c) height distribution of number of radiation events, (d) plan view, (e) east-westward vertical projection of lightning radiation sources. “*” indicates the time and location of the lightning initiation.

Almost 10,000 radiation sources were produced within a period of 15 min. The total number of lightning flashes was 33 and all of them occurred in thunderstorm 1. 25 of the 33 discharges were polarity inverted intracloud discharges and 8 are negative CG discharges. Compared to the developing stage, the radiation source density in the negative charge region in mature stage increased but with less horizontal extension as shown in Fig. 6c. The initial discharges of all the IC discharges were at the height of around 4 km, and the radiation sources concentrated in positive charge region between 1 km and 3 km high, similar to those during the developing stages. 7 of the 8 negative CGs initiated at the height of 4 km with 5 of them propagating directly downward to the ground, and 2 of them propagating first downward into the 3 km charge region and then horizontally along this charge region. The horizontal propagation lasted more than 90 ms and eventually formed a leader coming down to the ground. The remaining one negative CG can't be judged because of limited
number of located radiation sources. All these observed facts combined indicate that the charge structure of the thunderstorm during the mature stage remains the same as during the developing stage. The increase in the density of the radiation sources may suggest that the charge density has increased.

From 09:29 to 09:35 UTC, although the main cell of thunderstorm 1 was still in mature stage, its front began to dissipate. From 09:35 UTC, the main cell of thunderstorm 1 started to dissipate and merged with thunderstorm 2 as it moved eastward. The dissipation stage lasted until 09:58 UTC. As seen in Fig. 3, during the dissipation stage, some IC produced positive changes and some negative changes. Fig. 7 presents the mapping of the radiation sources from 09:29 to 09:58 UTC, where from 09:29 to 09:35 UTC the radiation sources only from the dissipating front of thunderstorm 1 were selectively displayed. Numerous radiation sources originated from the height of around 4 km and propagated upward in the initial dissipation stage. As shown in Fig. 7b and e, dense radiation sources concentrated above 4 km and the horizontal scale was approximately 3 km. This result indicates a small-scale positive charge region in the upper region (5–6 km, 09:29–09:34). Later, with thunderstorm 1 dissipating and attaching to thunderstorm 2, most lightning discharge mainly occurred between a 4 km negative charge region and a 3 km positive charge region (33 IC flashes), and most radiation sources were concentrated at approximately 3 km (09:35–
In the final 8 min, the radiation sources were observed to propagate from 1.8 km either upward, resulting in an IC, or downward, resulting in a negative CG.

As an example, Fig. 8 shows 2 individual IC flashes. IC1 and IC2 occurred at 09:38:01 UTC and 09:50:56 UTC, respectively. The flash of IC1 began at 4 km with negative-polarity breakdown ascending into a region at 5 km and then traveled horizontally. The horizontal propagation distance was about 3 km. After 100 ms, some radiation sources at 4 km descended and formed a downward channel propagating into a region at 3 km high. Then the radiation sources appeared on each of these two regions. For IC2, radiation sources indicate that a negative breakdown initiated at the height of 1.8 km and then ascended to a height of 3 km and propagated horizontally a few kilometers forming distinct stratiform structure as shown in Fig. 8b. During the dissipating stage, 7 IC1 types of discharges occurred between 4 km and 5 km charge region and 10 IC2 types of discharges occurred between 1.8 km and 3 km charge regions.

Fig. 9 shows the spatiotemporal structure of a negative CG lightning discharge. The lightning discharge lasted 500 ms and contained seven return strokes. "▼" indicated the timing of the first two return strokes. As seen in Fig. 9, the lightning discharge initiated at 2.2 km. Its leader developed directly to the ground and caused the first return stroke about 32 ms later. An attempted leader occurred between 09:33:52.724 and 09:33:52.791 with its initiation height also being about 2 km above the ground. The second return stroke occurred at
09:33:52.853 and its leader also initiated at 2 km. After the second return stroke, only a few radiations were produced during the dart leaders of the following subsequent return strokes. The lightning channels extended horizontally at the heights of around 2–3 km and exhibited bi-level structures during the time intervals between return strokes as shown in Fig. 9. The charge structures are similar to that of IC2 types of discharges, where the positive charge region is above the negative charge region. During the dissipating stage, 5 negative CG discharges occurred between 1.8 km and 3 km charge regions and 2 negative CG discharges occurred between 4 km and 3 km charge region. Only one negative CG discharges occurred between 5 km and 4 km charge region.

Based on the above results, it is inferred that the charge structure changed into four layers during the dissipation stage of thunderstorm 1. Before 09:35, the lower negative charge region was weak and the upper positive charge region was strong. After the 09:50, the lower negative charge region became strong and upper positive charge region became weak. So the negative charge region at 4 km and the positive charge region at 3 km are the prime charge regions, while the upper positive charge region at 5 km and the lower negative charge region at 1.8 km are two sub-charge regions.

3.3. The relationship of charge structure and radar echo

Fig. 10 shows the radiation sources (about 6 min) overlaid on the vertical cross-section radar echo at different stages of the thunderstorm. The pink ‘+’ stands for the radiation sources. As shown in Fig. 10a, the radiation sources were concentrated in 20–40 dBZ at the developing stage. The
negative charge region corresponded to the reflectivity in 35–50 dBZ, and the positive charge region corresponded to the reflectivity in 20–40 dBZ. In the mature stage, the updraft became strong, and the maximum reflectivity was 55 dBZ. The height with reflectivity greater than 50 dBZ reached as far as 5 km. A few radiation sources with a positive charge region were located in the 25 dBZ region at the beginning of the mature stage. Most of the radiation sources were located in the 35–50 dBZ region during the mature stage.

When the thunderstorm developed into the dissipation stage, as shown in Fig. 10c, the region of reflectivity greater than 50 dBZ gradually disappeared in thunderstorm 1. The charge structure transformed into four charge layers. Most of the radiation sources were located in the radar echo region of 20–50 dBZ. The lowest negative layer appeared in the echo region of 40–50 dBZ. The upper positive layer corresponded to 15–25 dBZ region, while the mid-level positive and negative layers were concentrated at 25–35 dBZ region.

4. Summary and discussion

An isolated thunderstorm that occurred on August 6, 2009, in Datong, Qinghai province, China, was studied using a 3D lightning mapping system distributed at seven stations. The 3D mapping results are summarized in Fig. 11. During the thunderstorm developing and mature stages from 09:08 UTC to 09:35 UTC when positive electric field was dominant, the thunderstorm took on an inverted dipole charge structure. During the thunderstorm dissipating stage from 09:35 UTC to 09:58 UTC, the charge structure changed into four layers of positive, negative, positive and negative charges with heights of 5 km, 4 km, 3 km and 1.8 km, respectively, though the charge structure may be subdivided into two cases according to the relative amounts of the corresponding charge as shown in Fig. 11. A comparison between the location of the lightning radiation sources and the radar echo shows that the radiation sources of the negative charge region corresponded to the
radar reflectivity about 40 dBZ in the developing and mature stages. The positive charge radiation sources were located in regions with a small radar reflectivity in the developing stage but in the mature stage the positive charge sources appeared in the regions with radar reflectivity greater than the 40 dBZ.

Based on fast antenna electric field changes, a total of 118 flashes were detected as shown in Table 1. During the dominant positive electric field period, 41 ICs and 9 CGs occurred. All IC occurred between the main negative charge region at 4 km and positive charge region at 3 km. Among the 9 CGs, 8 are negative and only 1 is positive. Earlier results (Clarence and Malan, 1957) indicated that the lower positive pocket charge is conducive to a negative CG flash in a normal summer thunderstorm because the local intense electric field produced by the pocket charge

Fig. 10. The left column figure is vertical cross-section radar reflectivity and the right column figure is radiation sources overlaid on vertical cross-section radar reflectivity. The symbol pink ’+’ stand for radiation source. (a) 09:05–09:10 UTC, (b) 09:27–09:32 UTC, (c) 09:44–09:49 UTC.

Fig. 11. Schematic idealization of the evolution of the thunderstorm electrical structure on August 6, 2009.
makes a negative streamer going down easily. Wang et al. (1990) analyzed the characteristics of ground discharges in an isolated thunderstorm with dominant positive electric field that occurred in Gansu province, China. They found that even the dominant charge structure is inverted, similar to our case in this study, majority of CGs are negative. A negative CG usually started as an inverted intracloud discharge lasting several hundred milliseconds. They speculated that the intracloud discharge part first neutralized the lower positive charge so that a hole in the positive charge region was formed and eventually led to a negative CG. Our results apparently support their arguments.

In the dissipation stage the number of positive CG increased with the ratio of negative CG to positive CG becoming 1:1. In the dissipation stage of the storm, the discharges inside cloud mainly occurred between lower positive charge region and 3 km and negative charge region at 1.8 km. With similar reason for occurrence of negative CG, such charge structure will be conducive to the occurrence of positive CG flash. Hamlin (2004) had studied a tornado storm and a supercell storm from STEPS and got similar observation results. Qie et al. (2005b) observed that negative CG flashes could be triggered frequently by a weak lower positive charge region in the late stage of the Qinghai–Tibet Plateau storm. It seems that not only the charge structure but also the intensity and polarity of lower charge region affect the number and the polarity of cloud-to-ground discharges.

Finally we should point out that the charge structure inferred in this study is different from those obtained by Qie et al. (2003, 2005a) and Zhang et al. (2009) for the similar type of storms that occurred in the same area. Qie et al. (2005a) used the surface electric field, and analyzed a sequence of 30 flashes in the thunderstorm. By using a point charge model, the height and magnitude of charge neutralized by return strokes in 16 negative CG and 2 positive CG flashes have been estimated with a nonlinear least-square method. The result indicated a tripole charge structure in the mature stage. This result is different with our results. Although the detailed reason for such discrepancy remains unknown, we have to point out two weak points of using 3-D lightning mapping system to estimate thunderstorm charge structures. As it is known, a 3-D lightning mapping system can only receive the radiation sources participating lightning discharge. Even an upper positive charge region does exist above the negative charge region, if the upper positive charge does not participate a lightning discharge, the 3-D lightning mapping system will not detect this charge. In addition, some positive discharges at the upper part of a thunderstorm may be too weak to be detected by the lightning mapping system. In the future, to better answer this question, we are going to analyze data sets collected from more such isolated thunderstorms.

Acknowledgments

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References


Table 1

<table>
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<tr>
<th>Time</th>
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<th>−CG</th>
<th>+CG</th>
<th>IC</th>
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<td>1</td>
<td>16</td>
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<td>8</td>
<td>8</td>
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