A Case Study of Cloud-to-Ground Lightning Activities in Hailstorms under Cold Eddy Synoptic Situation

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ABSTRACT

There were three hailstorms in Shandong Province, caused by a same northeast cold eddy situation on 1 June 2002. Cloud-to-ground (CG) flashes occurring in the weather event were observed by Shandong Lightning Detection Network (SLDN), which consists of 10 sensors covering all over Shandong Province. The temporal and spatial distributions of CG lightning are investigated for the three hailstorms by using the data from SLDN, Doppler radar and satellite. The results show that different thunderstorms present different lightning features even if under the same synoptic situation. The percentage of positive CG lightning is very high during the period of hail falling. CG flashes usually occurred in the region with a cloud top brightness temperature lower than -50°C. Negative CG flashes usually clustered in the lower temperature region and tended to occur in the region with maximum temperature gradient, while the positive ones usually spread discretely. Negative CG flashes usually occurred in intense echo regions with reflectivity greater than 50 dBz, while the positive CG flashes often occurred in weak and stable echo regions (10-30 dBz) or cloud anvils, although they can be observed in strong convective regions sometimes. Almost all hail falling took place in the stage with active positive flashes, and the peak positive flash rate is a little prior to the hail events. The thunderstorm could lead to disastrous weather when positive CG lightning activities occur in cluster. Severe thunderstorms sometimes present a low flash rate at its vigorous stage, which is probably caused by the “mechanism of charge region lift” through investigating the reflectivity evolution. Combined with the total lightning (intracloud and CG) data obtained by LIS onboard TRMM, the phenomenon of high ratio of intracloud flash to CG flash in severe hailstorm has been discussed. The competition of the same charge sources between different lightning types can also be helpful for explaining the cause of low CG lightning activities in severe storms.

Key words: hailstorm, cloud-to-ground (CG) lightning, echo intensity, brightness temperature, distribution characteristics

1. Introduction

Severe convective storms generally produce disastrous weather such as heavy rain, damaging gale and hailstone, as well as lightning. Lightning activity, as an indicator of strong convection, has been used to identify the developing convective cloud. Early observations revealed that thunderstorms with flash rate less than 10 fl min⁻¹ generally do not produce hailstone on the ground, whereas the flash rates in 60 percent of thunderstorms with hail falling were more than 100 fl min⁻¹ (see Shackford, 1960). Recently, with the rapid development of lightning detection technology, a lot of observations on convective weather events have been made by using lightning detection system and multi-parameter radars, and a great deal of meaningful results have been found. Reap and MacGorman(1989) found that the probability of large hailstone increased with positive cloud-to-ground (CG) lightning flash rate. Subsequent studies also revealed that large hailstones often occurred during the period of active positive CG lightning in thunderstorms producing predominately positive cloud-to-ground (PPCG) lightning (>50% +CG) (see MacGorman and Burgess, 1994; Stolzenburg, 1994; Chen, 1995). However, positive CG flashes were also apt
to occur in the period of dissipation or in the stratiform regions of mesoscale convective system (MCS), but the CG flash density and rate were obviously relatively lower (see Rutledge and MacGorman, 1988). After comparing hailstorms with ordinary thunderstorms observed in South Europe, Soula et al. (2004) discovered that the proportion of positive (POP) CG lightning was considerably high in hailstone-bearing storms, while the total CG flash rate was abnormally low. The total CG flash rates were no more than 2 fl min$^{-1}$ in hailstone-bearing storms, whereas they may be more than 12 fl min$^{-1}$ in thunderstorms just with heavy rain. Zhang et al. (2004) found that positive CG lightning predominated in the supercells observed, with the positive CG flash rate up to 6 fl min$^{-1}$. High POP sometimes occurred in some isolated storms (see Engholm et al., 1990; Carey and Rutledge, 1998). Additionally, Qie et al. (1998) also discovered that weak thunderstorms in Chinese inland plateau were often characterized by a relatively high ratio of positive CG lightning.

There are still some uncertainties on characteristics of temporal and spatial distributions of lightning in hailstorms. As yet, evolution of lightning activities and its relation to hail-falling in hailstorms are not well known, just as Williams (2001) pointed out that the relationship varies greatly with the discharge difference of thunderstorms that occurred at different latitudes, synoptic situations, and heights above sea level. In this paper, combined with Doppler radar and satellite data, the temporal and spatial distributions of lightning activity in a typical severe convective weather occurring in Shandong Province have been analyzed in detail. The purpose of this work is to disclose preliminarily the relationship between lightning activities and hail-falling, which would be helpful for the understanding of lightning characteristics in severe storms as well as the application of lightning information to the surveillance and warning of severe convective weather.

2. Data description

The CG lightning data used in the paper were obtained by Shandong Lightning Detection Network (SLDN), which consists of a central data processor located at the Electric Power Dispatch Center of Shandong Province, and 10 stations located in Liaocheng, Jining, Laiwu, Linyi, Weifang, Qingdao, Weihai, Longkou, Binzhou, and Dezhou. The distribution of SLDN stations is shown in Fig.1. The whole detection system was developed and installed by the Center for Space Science and Applied Research, Chinese Academy of Sciences. The SLDN uses the IMPACT (DF+TOA) method to determine the lightning location. Each CG flash record comprises such information as time, location, strength, polarity, etc. The theoretical values of location accuracy and detection efficiency are 500 m and 90%, respectively. The fault of high voltage transmission line caused by CG flashes also proved this location’s accuracy (see Liu et al., 1997). The data used in the paper are not corrected with detective efficiency.

The radar reflectivity data were obtained by Doppler radar in Binzhou, Shandong Province. The wavelength of the radar is 10 cm. In addition, IR1 data from the GMS5 satellite are also used in the paper.

3. Brief description of synoptic situation and statistical analysis of lightning

From 500-hPa air chart at 08:00 BT 1 June 2002 (figure omitted), it can be seen that Shandong Province was in the front part of the ridge of high pressure, and was controlled by northwesterly upper wind. Northeastern low vortex, which was relatively strong with a minimum of 5440 gpm, situated in the

![Fig.1. The locations of 10 lightning detection stations (marked with circle) and detection efficiency (isoclines) of Shandong Lightning Detection Network.](image-url)
East Heilongjiang Province. There was a west-east trough in the region of Beijing and Tianjin at 850-hPa level. Additionally, the unstable energy was accumulated due to high temperature up to 36 °C at the surface in the western and northern parts of Shandong Province on 31 May. The S, K, and CAPE at Ji’nan Station at 08:00 BT 1 June 2002 were -4.0°C, 29.0°C, and 1602 J kg⁻¹, respectively. Such synoptic condition with low vortex and zonal trough aloft was conducive to initiation and development of severe convective systems, regional hail-falling especially.

Figure 2 presents the spatial distribution of total CG lightning flashes observed by SLDN on 1 June 2002. It is easy to find from Fig.2 that three obvious CG lightning-clustered regions were in western, central, and eastern parts of Shandong Province, respectively. In western part, the CG flash density was the largest and most flashes were negative with the POP of 2.6%. The thunderstorms in the region only produced light rain. In central part, the CG flash density was relatively larger. The POP was the biggest with a value of 38%, and the local POP could be as high as 100%. The thunderstorms here produced not only light to moderate rain but also hail-falling. The positive CG flashes just clustered in the hail-falling regions. In the eastern part, the CG flash density was the smallest and the POP was about 12.5%. The thunderstorms here produced light rain. Through comparison with each other, it can be found that different thunderstorms could present different lightning features even under the same synoptic situation.

4. Case study

Based on surface observations, there were three hailstorm systems (denoted by Cases A, B, and C, respectively) which occurred serially in the northern part of Central Shandong Province from dawn to noon on 1 June 2002. They all produced hailstone and their individual characteristic values are presented in Table 1. The lightning activities in the three hailstorms are investigated in detail combined with Doppler radar and satellite data.

Table 1. Comparison of characteristic values for individual hailstorms

<table>
<thead>
<tr>
<th></th>
<th>Duration (h)</th>
<th>Min. TB (°C)</th>
<th>Max. Reflectivity (dBz)</th>
<th>Total CG</th>
<th>POP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>1.8</td>
<td>-59.4</td>
<td>65</td>
<td>38</td>
<td>7.9</td>
</tr>
<tr>
<td>Case B</td>
<td>1.5</td>
<td>-59.4</td>
<td>68</td>
<td>19</td>
<td>100</td>
</tr>
<tr>
<td>Case C</td>
<td>5.5</td>
<td>-64.8</td>
<td>71</td>
<td>491</td>
<td>50.3</td>
</tr>
</tbody>
</table>

4.1 Case A

Case A originated at about 45-km northwest of Binzhou Radar Station. A convective cell with a length of about 7 km and width of 2 km was observed at 01:17 BT. The maximum reflectivity was 35 dBz. The cell developed so fast that its reflectivity was up to 50 dBz in 3 min. At the same time, RHI observation revealed that the whole cloud developed vertically. Its cloud top was beyond 13 km, and the intense echo (>40 dBz) approached to 12 km. Subsequently, the first CG lightning occurred and its polarity was negative. By 01:30 BT, the thunderstorm further developed and five negative CG flashes produced (Fig.3a).

At 01:42 BT, the top of intense echo (>40 dBz) ascended above 12 km. Upper cloud began to spread out in all directions. It could be deduced that updraft dominated at middle to upper level of the storm, based on 60 dBz echoes being up to 9 km.

By 01:50 BT, the middle part of the radar echo on PPI stood out forwards and shaped a bow echo. There was only one CG flash (positive) lightning in
the period (Fig.3b). At this time, the storm continued to develop fast, and the top of 50-dBz echo was beyond 12 km (Fig.4a). According to soundings at Ji’nan Station, the core of 60-dBz echo was at a height of -40°C, suggesting that a mass of ice precipitation particles existed in the upper part of the cloud. There was obvious convergence at middle levels and very strong divergence at upper levels of the storm. It showed that intense updraft was still predominating at the middle to upper levels from the radial velocity image of RHI. Nevertheless, the radial velocity pattern at lower level was featured by divergence due to the effect of precipitation drag and evaporative cooling. By 02:02 BT, as the storm was approximately at its mature stage, the precipitation region began to expand largely. Only one positive CG flash occurred in this period (figure omitted). At 02:18 BT, owing to intensive precipitation, the area of strong echo >40 dBz at upper levels decreased apparently and the intense echo >50 dBz moved down thoroughly to lower levels (Fig.4b). It can be seen from Fig.4b that updraft still existed at middle to upper levels of the storm. From 02:32 BT the storm began to weaken and dissipate gradually. The whole storm fully disappeared on radar map by 03:04 BT.

Case A lasted for about 1 h and 50 min from 01:17 BT to 03:04 BT. It produced 38 CG lightning flashes, of which three were positive, during its lifetime. The time series of CG flash occurrence was presented in Fig.5. Seven minutes after the occurrence of the first positive CG flash, hail-falling was observed on the ground. The duration of hail-falling was about 3 min. The observation of lightning and hail showed that hail-falling took place in the period of active positive CG flashes.

4.2 Case B

Case B occurred from 08:00 BT to 09:00 BT in Guangrao County, 45-km southeast to Binzhou Radar Station. It produced hailstone with a diameter of about 1-2 cm. At 08:07 BT, the radar detected just a piece of weak echo. By 08:13 BT, the echo area expanded obviously with the maximum reflectivity of 44 dBz, but without CG flashes. At 08:23 BT, the convective cell developed quickly with the reflectivity up to 68 dBz (Fig.6a). Such intense reflectivity at lower levels suggested that large precipitation particles declined to lower levels (see Zheng et al., 2004a). Six CG flashes which occurred within 10 min were all positive. Most of them were distributed in the region with reflectivity larger than 45 dBz. The first CG flash, whose return stroke current was 30.1 kA, took place at 08:21:10 BT, just 5 min earlier than hail-falling. At 08:33 BT, the convective system kept on rapidly developing owing to mergence of a cell from north. The CG lightning flashes (no negative) were very active with the maximum flash rate of 12 flash min⁻¹ at this time. It was at the joint region of two cells where the CG lightning flashes were the densest (Fig.6b). Furthermore, a few positive CG flashes occurred in the region with reflectivity of 10-30 dBz around echo core. A large stratiform precipitation region in front of the system at this time became clear too. By 08:43 BT, the mergence of another cell from north led to expansion of intense reflectivity of >45 dBz and further enlargement of stratiform precipitation region in front of the system. Just only two CG flashes occurred in the weak echo around echo core. Subsequently, the system weakened gradually and did not produce lightning any more.

To sum up, Case B produced a total of 19 CG flashes, which were interestingly all positive. Hail-falling took place during the quickly going up period of positive CG flash rate. Positive CG flashes mainly occurred in the region with reflectivity larger than 45 dBz during the rapidly developing stage, whereas they were mainly distributed in the wide weak echo region around echo core during the mature and dissipation stage. Together with the cloud top brightness temperature from IR1, it can be found that all the positive
CG flashes occurred in the cold cloud region with temperature $<-50^\circ\text{C}$. Seimon (1993) also discovered that positive CG flashes clustered in the intense echo core and spread to all echo regions on occasion. The charge structure of Case B seems to be in an inverse dipolar structure based on all the positive CG flashes occurring during its lifetime. However, it is impossible to discuss the charge structure of thunderstorm in detail due to the lack of data of surface electric field and radar volume scan.

4.3 Case C

The severe hailstorm C, which took place east to Binzhou Radar Station from 09:00 to 13:00 BT, brought gust and hail damage to several regions. At 09:00 BT, Case C just was a new cell with a minimum cloud top brightness temperature of $-27.6^\circ\text{C}$. The maximum reflectivity was less than 38 dBz and there was no CG lightning in the early development stage. As the hailstorm moved southeastward at a speed of about 40 km h$^{-1}$, it developed rapidly. By 10:00 BT, the hailstorm had produced 16 CG flashes and all were positive. Most of them clustered in the front region with the brightness temperature $<-20^\circ\text{C}$. It can also be seen that CG flashes mainly occurred in the front weak echo area from radar PPI (Fig.7a). The weather system turned into squall line feature from 11:00 BT. Temperature gradient of the whole cloud was very large, and the temperature in the core was lowest with a minimum of $-60^\circ\text{C}$. The cloud top was up to a height of 14 km at this time. It produced 70 CG flashes, of which 39 were positive, within 30-min period. All CG flashes befell in the region with cloud top temperature less than $-50^\circ\text{C}$. However, the distribution pattern of CG flashes was not consistent with that of cold cloud cover with temperature $<-60^\circ\text{C}$ (Fig.8a). The cold cloud cover generally exaggerates the convective region, but lightning information can help us identify more accurately severe convective region. It is easy to find that there was a region with dense negative CG flashes in the front of cold cloud cover with temperature $<-50^\circ\text{C}$. Where were the negative CG lightning flashes from? By comparing with radar data, it was found that all the negative CG flashes were from a new cell, which was in front of the main intense echo area. Based on the experience that the dense negative CG lightning often corresponds to developing convection, one can speculate that the new cell had been intensified. The radar echo was indeed intensified in the later 15 min, just as anticipated. The new cell, which was impossible to be found just by means of cloud image, was possibly initiated by the outflow enforcement from the main thunderstorm.

By 12:00 BT, main cloud cluster expanded rapidly due to mergerence with the dissipating cloud from south. The area of cold cloud cover with temperature $<-30^\circ\text{C}$ was up to 5000 km$^2$. There were two cold cloud cores with temperature $<-60^\circ\text{C}$. The lowest temperature was $-64.8^\circ\text{C}$ at this time. Almost 69 CG flashes befell in the cold cloud cover $<-60^\circ\text{C}$. The CG flashes occurring in the back cold cloud core ($<-60^\circ\text{C}$) were all positive and distributed densely, whereas the CG flashes in the front cold cloud core contained both polarity and distributed sparsely. From the radar PPI superposed by CG flashes, it is found that positive CG flashes occurred in the intense reflectivity of rear system.

It is found clearly that Case C was a typical multicell storm lasting for 5.5 h. Figure 9 presents the time series of CG flash rate per 10 min of hailstorm C. It can be seen that all CG flashes which occurred during the early developing stage of hailstorm C were negative and distributed densely. Then CG lightning activity entered a quiescent period, without any CG flashes within 10 min. Most CG flashes from 09:30 to 10:00 BT were positive and its flash rate went up to 13 fl 10 min$^{-1}$. However, negative CG flashes dominated in the period of 11:00-12:30 BT. It shows that convection in this period was very active, because active negative CG flashes usually indicate, to some extent, intense updraft inside cloud (see Zajac and Weaver, 2002). After 14:00 BT the system began to weaken. The CG flash rate decreased remarkably, but the POP was very high in this period. According to surface observations of hail-falling, it was found that hail-falling took place in the stage with active positive flashes, and the peak positive CG flash rate was a little prior to the
Fig. 8. Distribution of CG flashes within 30 min superposed on cloud top brightness temperature contour at 11:00 BT (a) and 12:00 BT (b) in hailstorm C (‘+’ and ‘-’ stand for positive and negative CG flashes, respectively).

Fig. 9. Temporal variation of flash rate per 10 min in hail-storm C.

hail-falling. This is similar to the result of Carey and Rutledge (1995) that positive CG flash rate was going up 5-10 min ahead of hail-falling.

5. Conclusions and discussions

Based on the study of lightning activities in three hailstorms caused by the same northeast cold eddy, we can draw conclusions as follows:

(1) Three hailstorms occurring within a range of 60 km under the same synoptic situation could show different lightning activity. It indicated the diversity and complexity of lightning activity in thunderstorms. The difference was mainly caused by the small-scale enforcement of lifting or convergence at lower levels and its resulting individual difference of convection intensity. The three severe storms exhibited lightning characteristics as follows: In Case A, all CG flashes were negative during its development and dissipation stages, but positive ones occurring during its mature stage. The POP in its lifetime was 7.9%. In Case B, all the CG flashes in its lifetime were positive. In Case C, all CG flashes occurring in the development stage were negative, whereas positive and negative CG flashes alternated to predominate in the mature stage. At its dissipation stage positive CG flashes predominated again.

(2) CG flashes mainly occurred in the cold cloud region with temperature $< -50^\circ C$. Negative CG flashes were distributed densely and concentratively, while positive CG flashes distributed sparsely. The combination of lightning information and cloud image can be helpful to identify convection and precipitation regions.

(3) The CG flashes mainly occurred in the region with reflectivity $> 40$ dBz. Negative ones usually clustered in the intense echo region ($> 50$ dBz) or its close surrounding area, while dense positive CG flashes sometimes occurred in intense echo region, but sparse positive ones often occurred in weak and stable regions (10-30 dBz).

(4) Compared with surface observations of hail-falling, it was found that hail-falling took place in the stage with active positive flashes, and the peak positive CG flash rate was a little prior to the hail-falling. The thunderstorms could lead to disastrous weather such as hail or damaging wind when positive CG flashes occur in cluster.

Through the above analysis, it can be found that POPs in hail-falling period were very high, up to 100% on occasion. Nevertheless, the CG flash rates of hail-storms are relatively low. For example, Case A produced 38 CG flashes and just 19 for Case B. The maximum CG flash rate was yet less than 4 fl min$^{-1}$. 
Especially in Case A there was no any CG flashes within 20 min. Several researchers (see Maddox et al., 1997; Lang et al., 2000; MacCaul et al., 2002) also found the same phenomenon.

Electrification and discharge are tightly associated with updraft. Firstly, updraft can accommodate supercooled water, which plays a fundamental role in ice growth, especially for graupel particles. The collisions between ice particles are considered necessary for charge transfer. Secondly, intense updraft is in favor of charge separation to form different charge zones in cloud. Therefore, lightning activity is closely related to the development of severe convective weather.

Take Case A as an example. At 01:52 BT, intense echo core with reflectivity $>60$ dBz was in the height range from 8 to 10 km, -30 to -45 °C for temperature. It is obvious that such intense reflectivity was caused by graupel, hailstone, and large raindrops. Abundant graupel and hail particles in upper levels of cloud imply a great deal collisions between graupel and ice particles. Therefore the electrification in cloud must be violent. In the case of abundant supercooled water, graupel particles charge negatively as a result of graupel-ice collisions. Strong updraft not only results in the intense electrification, but also lifts the main negative charge level. Consequently this can result in enlarging the distance from negative charge region to ground, and reducing the distance between negative and upper positive charge regions. The Lightning Imaging Sensor (LIS) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite provides the total lightning activity with information of occurrence time, latitude, longitude, and radiant energy of both CG and IC lightning flashes (see Qie et al., 2003). The TRMM satellite can view a storm for about 90 s because it runs around the earth at a speed of about 7 km s$^{-1}$. Fu et al. (2003) and Zheng et al. (2004b) have studied the precipitation structures and lightning activities of heavy rain cases and their relations. In order to examine the CG and IC lightning characteristics in severe thunderstorms, we look over all TRMM’s orbits nearby, and found that the TRMM satellite scanned (orbit number 25917) a hailstorm occurring near Binzhou Radar Station on 29 May 2002, not 1 June 2002. Figure 10 shows that there were 127 flashes in the southwest thunderstorm in the period of 1 min and 4 s, whereas just 4 CG flashes (one positive and three negative) were detected by SLDN within the same period. Thus the ratio of IC to CG flashes was about 31:1. Carey and Rutledge (1998) found that the ratio was up to 70:1 in one severe hailstorm. Thus it can be seen that severe storms may have intense intracloud discharge activity with lower CG flash rate. Williams et al. (1999) also noted a tendency that CG is often suppressed when IC is active, a so-called competition of the same charge sources between different lightning types.

Lightning activities in the three hailstorms further reveal that lightning information is, to some extent, helpful for warning and forecasting of severe weather. However, thorough understanding of lightning activities in severe thunderstorms still demands more investigation, especially careful examination of many individual cases by combining total lightning information with radar, satellite, and routine
synoptic data, so that we can grasp the general features of different thunderstorms, which would be necessary to the application of lightning information to the warning and nowcasting of severe convective weather.

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