Analysis of Lightning Characteristics in a Thunderstorm with Gust

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Abstract

One severe thunderstorm with damaging straight-line wind occurred on 21 June 2005 in north Shandong Province. Based on the analysis of lightning activities, radar echo and cloud image, it was found that the cloud-to-ground (CG) flash rates increased rapidly at the initial stage, and kept in a high level (about above 20 fl/5min) during the whole mature stage. At the dissipating stage, positive CG flashes gradually became dominant. For the advent of the peak value, the hourly flash rate lagged behind the minimum brightness temperature, and the area of cold cloud shield with temperature <-50°C lagged behind the hourly flash rate. The pulse of CG flash rate was slightly ahead of the occurrence of severe surface wind. Downburst caused the damaging wind with the maximum measured value of wind speed approximately the same to the maximum potential speed calculated by WINDEX.

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Keywords: Mesoscale convective system Cloud-to-ground lightning Damaging wind Doppler radar

1. Introduction

Mesoscale convective systems (MCS) are usually associated with severe weather phenomena, and they often bring heavy rain, hailstone, lightning, strong winds and even tornadoes and downburst. Since the updraft in MCS is very violent, the corresponding electrification and discharge process within cloud is
very active too. In recent years, with rapid development of lightning detection technology, the adequate information of lightning flashes of severe convective weather process has been obtained by means of lightning locating systems. And many significant results (zhang et al., 2006; Qie et al., 2005) on lightning activities have been made. It was found that lightning data can effectively improve the accuracy of forecast and diagnosis of severe convection weather. The percentage of positive CG in severe convective weather systems with hail or strong wind is obviously higher than ordinary thunderstorms (Reap et al., 1989; Stolzenburg, 1994; MacGorman et al., 1994; Chen, 1995). Hailstone usually occurs in the active stage of positive CG (Feng et al., 2008). In recent years, the situation becomes increasingly serious because of the more and more disasters caused by severe thunderstorms. The downburst which can lead to damaging straight-line wind has also been a important and key point for weather forecast. In order to further understand the lightning characteristics in mesoscale thunderstorm, the lightning characteristics of a MCS process was analyzed based on compositive data observed by lightning location system.

2. Introduction of synoptic situation and data used

At 08:00 (Beijing Time) on June 21, 2005, there was a low pressure circulation in the middle of the Northeast China at 850hPa, 700hPa and 500hPa layers. The low pressure’s center was in north of Changchun, and at both 700hPa and 850hPa the temperature ridges are accompanied by the height ridges. By 20:00, at 500hPa the NNW flow increased significantly in front of the ridge, while the speed increased 6m·s\(^{-1}\) compared with 08:00. The temperature ridge strengthened and moved eastward at 700hPa and 850hPa, and in the front of the warm ridge an east-west shear formed near Beijing at 850hPa. The significant warming from the lower to the ground increased the atmospheric vertical instability. The increase of the wind speed at 500hPa led to the enhancement of the vertical wind shear, and the unstable energy was triggered to release because of the convergence at both the low-level and the ground. All of above factors resulted in a mesoscale convective systems occurring in the region of North and Middle of Shandong Province, which was accompanied by strong winds and lightning from the night of June 21 to 22. The largest wind speed was up to 28.5m\(^{-1}\) in four townships of Boxing at 22:30 on June 21.

At 20:00, sounding data at Zhangqiu station (east of Jinan) showed that the convective available potential energy (CAPE) was 739J \(\cdot\) kg\(^{-1}\), K index was 35.0 \(^{\circ}\)C, the total index of TT was 51.0 \(^{\circ}\)C, and the vertical wind shear of 0-6km was 18.4m\(^{-1}\). All these indicators were up to the conditions of severe thunderstorms.

The CG flash data used for this paper were provided by Shandong lightning location systems, and the radar data are provided by the two Doppler radars situating in Jinan and Binzhou respectively. Details about the lightning location network were presented in Feng et al. (2006).

3. Characteristics of lightning activity

There were 1220 CG flashes in the whole lifetime of the MCS. The positive CG flashes took up the percentage of 18.2%. The minimum, maximum and average values of return current intensity of positive CG were 7.0kA, 169.6kA and 33.22kA, respectively. For negative CG peak current intensity: the minimum value -2.7kA, the maximum value -49.4kA, and the average value -10.29kA. There were only 2 positive CG flashes with current intensity less than 10kA. Cummins et al. (1998) thought that the positive CG flashes with current intensity less than 10kA were usually intracloud flashes because of observation system’s mistake. According to this view, the flash data of this system is available. From the distribution of the positive and negative CG flashes, it can be seen that the maximum peak current intensity and the average one of positive CG flashes were 3 times higher than that of negative CG flashes.
From Fig.1, it can be found that the MCS developed rapidly after making landfall from the northern coast of Binzhou. Accompanying with the strong convection, the corresponding flash activities also jumped. The maximum rate was 25 flashes/5min. At a later time, the CG flashes had taken on a rising trend. From 22:25 to 22:30, the flash rate rose suddenly to 42 flashes/5min from 24 flashes/5min, and in the next 30 minutes the CG flash rate maintained 30 flashes/5min or more. At 22:30, a 10 degree wind was observed by ground-based observation, which was caused by strong downdraft outflowing from the bottom of the thunderstorm. It suggested that the CG flash rate jump occurred 5 minutes ahead of the strong surface winds. However, the positive CG flashes rate started to increase after the strong wind of the ground emerged, and meanwhile the proportion of positive CG flash increased. The positive CG flashes in the period from 00:10 to 01:00 were most active, with an average rate of 10 flashes/5min and the maximum rate of 15 flashes/5min. After 01:00 the positive CG flashes started to decrease. At around 00:50, the negative CG flash rate came to a peak. Corresponding to the radar data, it can be seen that a new convective cell in front of MCS produced many negative CG flashes, and then the new convective cell merged into the parent thunderstorm. So the convective activity of the system enhanced slightly and generated dense negative CG flashes relatively (Fig. 3b).
4. The relationship between lightning activities and cloud images and the relationship between lightning activities and radar echoes

From GOES9 hourly satellite images it can be found clearly a loosely organized cumulus cloud cluster at the junction of Hebei Province and Liaoning Province near Bohai Bay, and then the cloud cluster developed rapidly while moving southward. By 20:00, the cloud cluster developed into dense oval shape. The minimum brightness temperature of the top cloud was -57.1 °C, and the clouds area with brightness temperature lower than -30 °C covered up to 47000km². The surface temperature at 21:00 was just over 30 °C in Northern Shandong, which was controlled by warm low-pressure with the minimum central pressure less than 998.9hPa. The rapid expansion of the cloud cluster appeared around 22:00. The area of cloud with brightness temperature lower than -30 °C and -50 °C was 65000km² and 34500 km², respectively. The minimum cloud top brightness temperature was -60.9 °C (Fig. 2a). By 00:00 on June 22, the minimum cloud top brightness temperature slightly increased to -58.3 °C, but the clouds continued to expand to the surrounding. Then the system began to weaken, and the area covered by cloud lower than -50 °C began to decrease. At last this weather system disappeared completely after 06:00.

From the superposition of lightning and cloud Images (Figure 2) it can be found that the CG flashes mainly appeared in the front of the system. Most lightning flashes occurred in the area of cloud with top temperatures below -40 °C, and only the individual flashes fell in the cloud area above -30 °C. For the spatial distribution of CG flashes, the negative CG flashes were relatively denser, however the positive CG flashes were sparse and located in the back of the area of negative CG flashes.

The cold cloud area increased with the increase of CG flash rate. By 23:00, the CG flash rate reached a peak of 414 flashes·h⁻¹. The cold cloud area reached the maximum (for 41100km²) 1 hour later. Then the area cover of cold cloud decreased as the number of CG flashes decreased. From the distribution curve of the minimum cloud top temperature, it can be seen that the minimum cloud top temperature had been declining from 19:00 to 22:00, and reached the minimum value of -60.9 °C at 22:00. The minimum cloud top temperature started to rise after 23:00. According to the advent of peak time, the hourly CG flash rate lagged behind of the hourly minimum cloud top temperature, and the hourly cold cloud coverage lagged behind of the hourly CG flash rate.

Figure 3 shows the overlay chart of the Qihe Doppler radar combination reflectivity and 10-minute of CG flashes on June 21, 2005. It clearly shows that the CG flashes were mainly in the region with echo more than 20dBz. The negative CG flashes were mainly in more than 25dBz, corresponding to the convective precipitation region; however the positive CG flashes mainly occurred in less than 25dBz echo area, corresponding to the stable stratiform precipitation region.

![Figure 3. The evolution of Qihe Doppler radar compositive reflectivity and CG flash distribution on June 21, 2005. a: 22:51; b: 00:52:17. “+” and “-” represent positive and negative CG flashes within 10min, respectively.](image-url)
5. Analysis of the strong wind

The MCS showed obvious features of the bow echo (Fig. 4a). The strongest downdraft of thunderstorms often occurs in the front of the center of the bow echo. Hourly observation showed that the maximum of the wind speed (27.5 m·s⁻¹) appeared slightly in front of the strong echo (50 dBz). The radar echoes (22:00 June 21, 2005) from Qihe and Binzhou Doppler radars clearly showed the outflow boundary in the front of the MCS, indicating that thunderstorms had entered a mature stage. The outflow boundary was featured as a narrow strip echo with about 6 km width and about 2 km height on the radar echoes intensity image at low elevation (0.5), whereas it was featured as a low layer convergence zone on the velocity image. Outflow boundaries of thunderstorms in the satellite image usually present of arc-shaped Cumulus line (Bader et al., 1995). At 01:00 and 02:00 on June 22, since the thunderstorm weakened and dissipated, the arc-shaped convective cloud line was clearly identified, and was away from the parent thunderstorm about 70 km. As the moving speed of outflow boundary was greater than that of the parent thunderstorm, the warm and humid air flowing into the parent thunderstorm was cut off. Then it accelerated the demise of the parent thunderstorm. Through the above analysis it could be drawn that the disaster wind of the MCS was mainly caused by the strong outflowing downdraft at the bottom of the thunderstorm.

At 22:39, the strong precipitation center was right over Binzhou radar station. The velocity image of Doppler radar (Figure 4) clearly revealed that the northeast wind prevailed at the lower layer. With the height increasing, the northeast wind reversed to the northwest wind, indicating that cold advection dominated in the whole layer. The middle layer at the height of 5-6 km showed significant convergence characteristics, and the layer above 9 km demonstrated divergence characteristics, indicating that the middle and the upper layers of the convective clouds was still controlled by the updraft. The layers of 2.5-5.0 km were controlled by the strong north wind, and the maximum wind speed (up to 36 m·s⁻¹) center was at the height of 3.5 km. This was the so-called cold and dry inflow at the rear parts of the middle layer, which led to the bow-shaped echoes. The cold and dry downdraft caused local wind disasters. In Binzhou station, atmospheric pressure increased 6.2 hPa, and the temperature decreased 8.5 °C.

Using four-dimensional variational assimilation technique for single Doppler radar, three-dimensional wind field was retrieved (Mu et al., 2007). Figure 5 is the horizontal flow field of 1 km height and reflectivity chart. At the position of 140 km northeast to the radar station (coordinates is 105, 97), there was a clear divergence center, which indicating that the downdraft center was at the back of strong echo. The speed of outflowing air was significantly accelerated after moving forward through the strong echo zone. Then it could be demonstrated that the downdraft acceleration was caused by the drag effect and evaporation cooling effect of precipitation particles.

Figure 4. Radial velocity of Binzhou Doppler radar at 22:39. Elevation angle is 14.6°

Figure 5. The distribution of reflectivity and horizontal wind fields retrieved at 1 km height at 22:51.
To further analyze the causes of the strong winds, a kind of wind index-WINDEX was introduced in the paper, which was presented for the prediction of downburst winds by McCann (Sun 2004). The empirical index reflects the possible interaction affection on ground damaging wind of temperature and humidity characteristics at middle and lower layers to ground winds. The expression of WINDEX is,

$$WINDEX = 5[H_0 R_0(\Gamma^2 - 30 + Q_L - 2Q_M)]^{0.5}$$

Where $H_0$ is the height of 0°C layer above ground level, in km as a unit, $R_0 = Q_L/12$, but not more than 1g·kg$^{-1}$, the $\Gamma$ is the lapse rate between ground and 0°C layer ($^\circ$C·km$^{-1}$), $Q_L$ is the average mixing ratio from ground to 1km height (g·kg$^{-1}$), $Q_M$ is mixing ratio of 0°C layer; the units of WINDEX is knot (miles/hour), but it could be transformed into m·s$^{-1}$ multiplied by 0.5147.

Used the sounding data (20:00, on June 21) of Zhangqiu, the WINDEX was calculated to 28.55 m·s$^{-1}$, that reached the standard of 11 degree wind. At 22:42, the maximum wind speed of Gaoqing weather observation was 27.5 m·s$^{-1}$ (up to the 10 degree wind). So the calculated value is very close to the real value.

6. Conclusion and discussion

Based on the analysis of the causes of the CG flash activities and damaging winds of the MCS, the conclusion was drawn as follows:

(1) In initial development stages of MCS, the CG flash rate rose rapidly, then it maintained a high value in the mature stage. In the dissipation stage, the CG flash frequency decreased rapidly. Most of the CG flashes in the MCS were negative, but only in the weakening stage the proportion of positive CG flashes began to increase, which was even more than that of negative CG flashes on occasion.

(2) Negative CG flashes mainly occurred in the convective region with the reflectivity >25dBz, while positive CG flashes mainly occurred in the region with the reflectivity <25dBz, corresponding to the stable stratiform precipitation areas.

(3) According to the advent of peak time, the hourly CG flash rate lagged behind of the hourly minimum cloud top temperature, and the hourly cold cloud coverage lagged behind of the hourly CG flash rate. This implied that the lightning activities also continued to enhance when the storm developed to the maximum cloud-top height. After the flash rate per hour reached peak value, the cloud top of thunderstorm continued to extend outward.

(4) The damaging wind corresponded to severe lightning activities, so it primarily indicated that the lightning activities may be regarded as an indicator for the severe wind. When the MCS appeared bow-shape echoes and the CG flash rate was very high, it was supposed to pay more attention to the severe ground winds caused by downburst.

(5) The maximum wind speed observed at weather station was approximate to the maximum potential speed calculated by WINDEX. So WINDEX has potential value for the prediction of thunderstorm downburst.

The reasons of fourth result were discussed as follows. In the normal tripole charge structure, the presence of weak positive charges in the low layer can increase the local electric field. So it is conducive to the occurrence of negative CG flashes (Jacobon and krider 1976). This opinion has been recognized by more and more researchers. One-dimensional and two-dimensional convective cloud models with electrification confirm that if the low-layer positive (negative) charge participate in the discharge, the negative (positive) CG flashes could be more likely to occur (Sun et al., 2001; Marshall and Stolzenburg 2002). Mansell (2002) used a more detailed three-dimensional simulation and found that if the low layer charge region is not present, the positive and negative CG flashes couldn’t happen. This opinion has been confirmed further by field observations (Wiens et al., 2005), and the CG discharges mainly originated from the range 5~9 km altitude. At 21:45, the top of the echo was up to 14.6km, the strong echoes area
with reflectivity more than 40dBz was up to 12km. In the strong ground wind periods, the echo top declined to 12.0km, the strong echoes area with reflectivity more than 40dBz declined to 6.5km. The storm centroid went down from 7km to 3km. With the decline of the storm centroid, the charge zones of thunderstorm also bounded to decline. Then it shortened the distance between the main negative charge region and the ground. Therefore it became easy to transport the negative charges to ground to produce negative flashes. From the above analysis it can be found that the strong winds stage corresponds to severe flash activities, and further clarified that the lightning activities may be regarded as an indicator for the disaster weather.

Although the above analysis initially presents the certain values of lightning information for the warning and forecast of the convective disaster weather, however, more cases need to be accumulated to comprehensively understand the electrification and discharge activity of thunderstorms. Particularly, intracloud flashes information should be taken into consideration in order to deepen the whole understanding of the rules of thunderstorm discharges.

6. References