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Spatial–temporal characteristics of lightning flash size in a supercell storm

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ABSTRACT

The flash sizes of a supercell storm, in New Mexico on October 5, 2004, are studied using the observations from the New Mexico Lightning Mapping Array and the Albuquerque, New Mexico, Doppler radar (KABX). First, during the temporal evolution of the supercell, the mean flash size is anti-correlated with the flash rate, following a unary power function, with a correlation coefficient of -0.87. In addition, the mean flash size is linearly correlated with the area of reflectivity $>$ 30 dBZ at 5 km normalized by the flash rate, with a correlation coefficient of 0.88. Second, in the horizontal, flash size increases along the direction from the region near the convection zone to the adjacent forward anvil. The region of minimum flash size usually corresponds to the region of maximum flash initiation and extent density. The horizontal correspondence between the mean flash size and the flash extent density can also be fitted by a unary power function, and the correlation coefficient is $>$ 0.5 in 50% of the radar volume scans. Furthermore, the quality of fit is positively correlated to the convective intensity. Third, in the vertical direction, the height of the maximum flash initiation density is close to the height of maximum flash extent density, but corresponds to the height where the mean flash size is relatively small. In the discussion, the distribution of the small and dense charge regions when and where convection is vigorous in the storm, is deduced to be responsible for the relationship that flash size is temporally and spatially anti-correlated with flash rate and density, and the convective intensity.

1. Introduction

The relationship between flash activity characteristics and thunderstorm structure is a core issue in research into the electrical properties of thunderstorms, and provides the theoretical basis for lightning forecast, early warning and data assimilation. Previous studies have produced remarkable results on the correlations between the evolution of thunderstorm structure and flash rate, location, and polarity characteristics. For example, it has been suggested that there is a positive correlation between total flash rate and thunderstorm intensity (Carey et al., 2003; Deierling and Petersen, 2008; MacGorman and Morgenstern, 1998), that severe thunderstorms are more likely to have lower cloud-to-ground (CG) flash ratios and higher positive CG flash ratios than normal thunderstorms (Carey and Rutledge, 1998) and that a higher proportion of CG flash activity occurs during the dissipation phase of thunderstorms (Schultz et al., 2011).

In addition to the flash rate, polarity, and location, flash size is also an important parameter that can describe the development of flashes. If the propagation of the flash occurs in the charge regions of the thunderstorm, the flash size can indicate features of the charge distribution. Therefore, including flash size in studies of thunderstorm electricity will lead to further understanding of the characteristics and mechanism of lightning activity. In recent years, with the development of three-dimensional lightning detection technology at VHF (Very High Frequency), VLF (Very Low Frequency) and LF (Low Frequency), some studies have started to investigate flash size and its correlation to thunderstorm structure. Bruning and MacGorman (2013) showed that flashes in or near the strong updrafts tended to be frequent and that the flash size (area of the convex hull of the horizontal projection of VHF source points that belong to the same flash) in this region was small, while flashes far from strong vertical drafts exhibited the opposite tendency. Chronis et al. (2015) found that the diurnal variation of flash size (maximum horizontal and vertical extent) closely matched the diurnal variation of the peak current of cloud-to-ground flashes. Zheng

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and MacGorman (2016) reported that the largest flashes occurred in the adjacent forward anvil of the supercell, while the flashes near the updrafts were smaller and more frequent.

In general, flash size is a relatively new descriptive parameter for flash activity in thunderstorm-weather electricity research. In this study, the relationships between flash size, the intensity of flash activities and the spatial–temporal evolution of the thunderstorm structure are discussed, based on both qualitative and quantitative analyses of the supercell in New Mexico on October 5, 2004. This study aims to deepen our understanding of the mechanisms responsible for the formation and development of flash activity in severe storms.

2. Data and methodology

2.1. Lightning data

The lightning data for the supercell in New Mexico on October 5, 2004 are from the New Mexico Lightning Mapping Array (LMA). Ten sub-stations are involved in positioning the flashes in this supercell. The central frequency of the LMA is 63 MHz, with a bandwidth of 6 MHz. For the flashes inside the network, the horizontal positioning error of the LMA is 6–12 m, and the vertical error is 20–30 m (Thomas et al., 2004). Details of the LMA can be found in Rison et al. (1999), Krehbiel et al. (2000) and MacGorman et al. (2008). The supercell analyzed in this paper is located within 100 km of the center of the station network where the three-dimensional positioning results are relatively more reliable (Fig. 1 shows the LMA 100 km detection range and the general trajectory of the supercell).

The positioning results were filtered following Lund et al. (2009) with the condition that the radiation sources must be located by at least seven sub-stations and the chi-square goodness-of-fit value $\chi_{\nu}^2 \le 2$. The algorithm for reconstructing an individual flash from sources (a flash is made up of sources that meet certain conditions) was introduced by MacGorman et al. (2008) and Zheng and MacGorman (2016). In this study, a potential flash source must occur within 180 ms of the previous source and within 2 km and 300 ms of any other flash source, and any flash that contains < 10 points is excluded. As in the initial position algorithm of Lund et al. (2009), the initial point of a flash is calculated as the centroid of a compact cluster of the initial 10 points and the time of the first source of the flash is determined as the initial time of the flash.

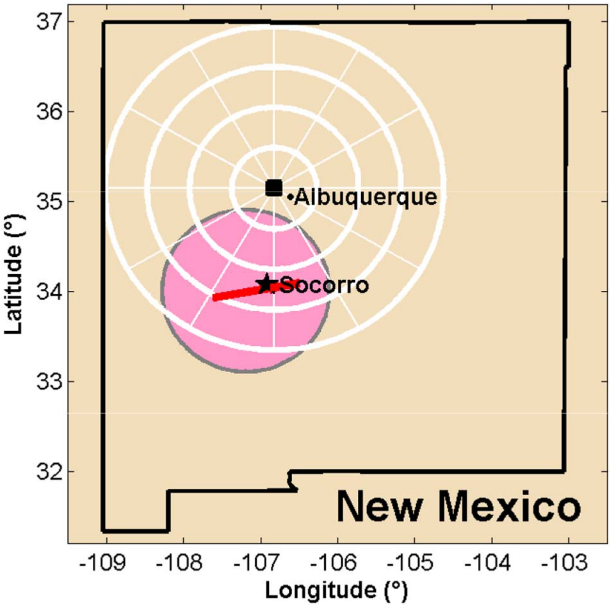

Fig. 1. Albuquerque WSR-88D radar and LMA detection range. The black rectangle represents the position of the Albuquerque WSR-88D radar. The small black dot represents the position of the Albuquerque sounding station. The black star represents the hail location. White lines indicate the radar detection ranges of 50 km, 100 km, 150 km, and 200 km. The pink circle is the 100 km reliable detection range of the LMA, and the red line corresponds to the trajectory of the supercell. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

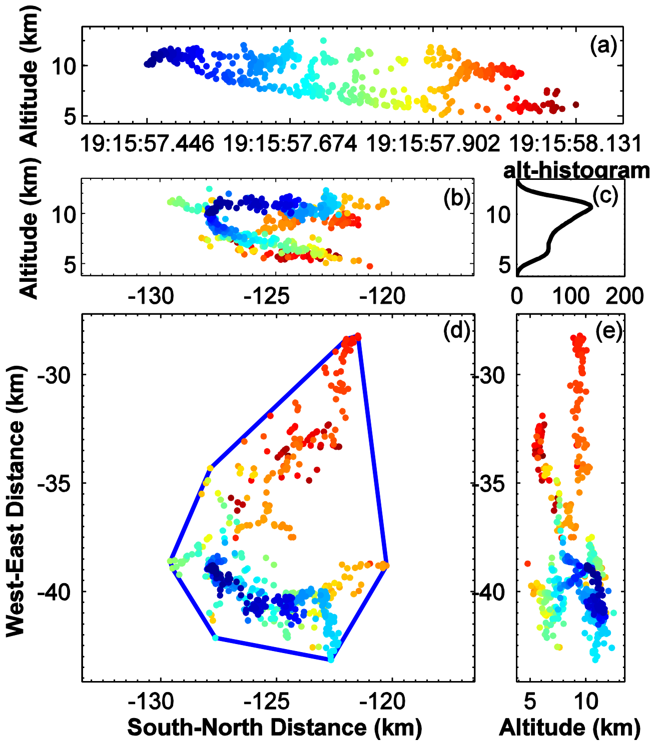

Fig. 2. Example of a flash at 1915:57 UTC and its corresponding flash size. (a) Altitude and time distribution of LMA sources. (b) Altitude and south–north distribution of LMA sources. (c) Frequency of sources at different heights. (d) Horizontal distribution of LMA sources. (e) Altitude and west–east distribution of LMA sources. In all figures the position of the radar station is taken as the origin of the coordinates.

Flash size is represented by the area of the convex hull of the horizontal projection of VHF source points, as applied in several studies (Bruning and MacGorman, 2013; Zheng and MacGorman, 2016). Each flash corresponds to the area of the convex hull that contains all source points of the flash, as shown in Fig. 2d. The area surrounded by the blue solid line is the convex hull area corresponding to the flash at 1915:57 UTC. To investigate the lightning activities in different spatial regions of supercell, parameters of flash initiation density and flash extent density are introduced in this study. Flash initiation density counts the number of the flashes that begin within a spatial grid box; and flash extent density counts the number of flashes passing through a spatial grid box (e.g., Bruning and MacGorman, 2013).

2.2. Radar data

The Albuquerque, New Mexico, Doppler radar station (KABX) provides the base data on reflectivity and radial velocity of the supercell. The KABX radar is located about 130 km east of the center of the LMA systems (Fig. 1a). The storm moved within 100 to 150 km of the radar station. For the convenience of analysis, the reflectivity data are bilinearly interpolated onto a rectangular coordinate system with a horizontal resolution of 0.4 km and a vertical resolution of 0.5 km. When overlaying lightning and radar data, the lightning data are extracted during the period of a radar volume scan (5 min 14 s) so as to match with the radar data at that time.