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Charge structure analysis of a severe hailstorm with predominantly positive cloud-to-ground lightning

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ABSTRACT

The present study makes use of cloud-to-ground lightning, three-dimensional mapping from a Lightning Mapping Array and Doppler C-band radar observations to analyze the lightning trends and the underlying electrical charge structure of a large-hail bearing storm that produced important damages on the local agriculture. The analysis reported an extremely active storm, evolving through distinct phases, which stood out from a multicell structure to finally become a supercell. The onset of newer regions of convective development interacting with the main cell made the charge structure to be rather complex during some stages of this long-lived hailstorm. Evidence suggests the presence of regions with the charge layer being inverted from that of normal, non-severe convective storms, producing predominantly positive cloud-to-ground lightning. The analysis also suggests that strong cloud signals were misclassified as low peak current single-stroke negative cloud-to-ground flashes, masking the predominant positive nature of the storm.

1. Introduction

Hail has a great impact on the Lleida Plain, an agricultural area in the Mid-Ebro River Valley (MEV), located in the north east of the Iberian Peninsula (Fig. 1). The high frequency of hailstorms, including some severe convective events that hit the region almost every year, generates important losses on the local economy (López and Sánchez, 2009). For this reason, the area is specially monitored (e.g. hailpad networks) and a long list of studies can be found in the literature related to hail in the MEV. These works range from climatology to case studies. Some dealt with the characterization of synoptic environments (e.g. García-Ortega et al., 2011; Merino et al., 2013) and mesoscale factors leading to the onset of deep convection (e.g. Romero et al., 1998; García-Ortega et al., 2012). Others focused on the analysis of the thermodynamic conditions (e.g. Palencia et al., 2010; Gascón et al., 2015), as well as on the representativeness of the nearby soundings (e.g. Romero et al., 2001; Aran et al., 2007). The role of the local topography has also been analyzed (e.g. Font, 1983; Castro et al., 1992; Tudurí et al., 2003). Besides, significant events have been analyzed using remotely sensed data (e.g. Ceperuelo et al., 2006; Pineda et al., 2009; Rigo and Llasat, 2016). Regarding lightning patterns on hailstorms, Montanyà et al. (2007) observed high intra-cloud (IC) flash rates, combined with low cloud-to-ground (CG) flash rates during whole storm lifetime. Moreover, no positive CG (+CG) were reported. In another severe hail-bearing storm, Montanyà et al. (2009) also observed high IC flash rates, but in this occasion +CG were dominant in some phases of the storm. Besides, negative CG (−CG) presented very low peak currents and a multiplicity (strokes per flash) close to one. Soula et al. (2004) reported a similar pattern for the -CG peak currents in hail events occurred in the south of France. Pineda et al. (2009) observed large IC rates prior to the severe convective weather, followed by a decrease of the lightning activity during the hail shaft. Different hypotheses concerning the particular lightning trends in hail-bearing storms and the underlying electrical charge structure were discussed in these studies, but the lack of observations about the vertical distribution and heights of the charge layers made difficult to validate those hypotheses.

Observational evidence (e.g. Reap and MacGorman, 1989; Branick and Doswell, 1992; Curran and Rust, 1992; Seimon, 1993; MacGorman and Burgess, 1994; Stolzenburg, 1994; Carey and Rutledge, 1998; Lang et al., 2004; Soula et al., 2004; Wiens et al., 2005) suggests that severe thunderstorms which produce large hail (diameter > 2 cm) and sometimes tornadoes are often characterized by a predominance of positive CG (PPCG) lightning for extended periods of time (≥30 min) during the mature phase. Carey and Rutledge (1998) noticed that the +CG lightning flashes, in these severe thunderstorms, are clustered in time and space in or near convective regions similar to negative CG flashes in ordinary storms and have comparable flash densities.

However, severe weather may occur without dominant +CG flash activity (e.g. Williams, 2001; Carey and Rutledge, 2003). Overall, the CG flash rate and the CG polarity in severe convective storms present

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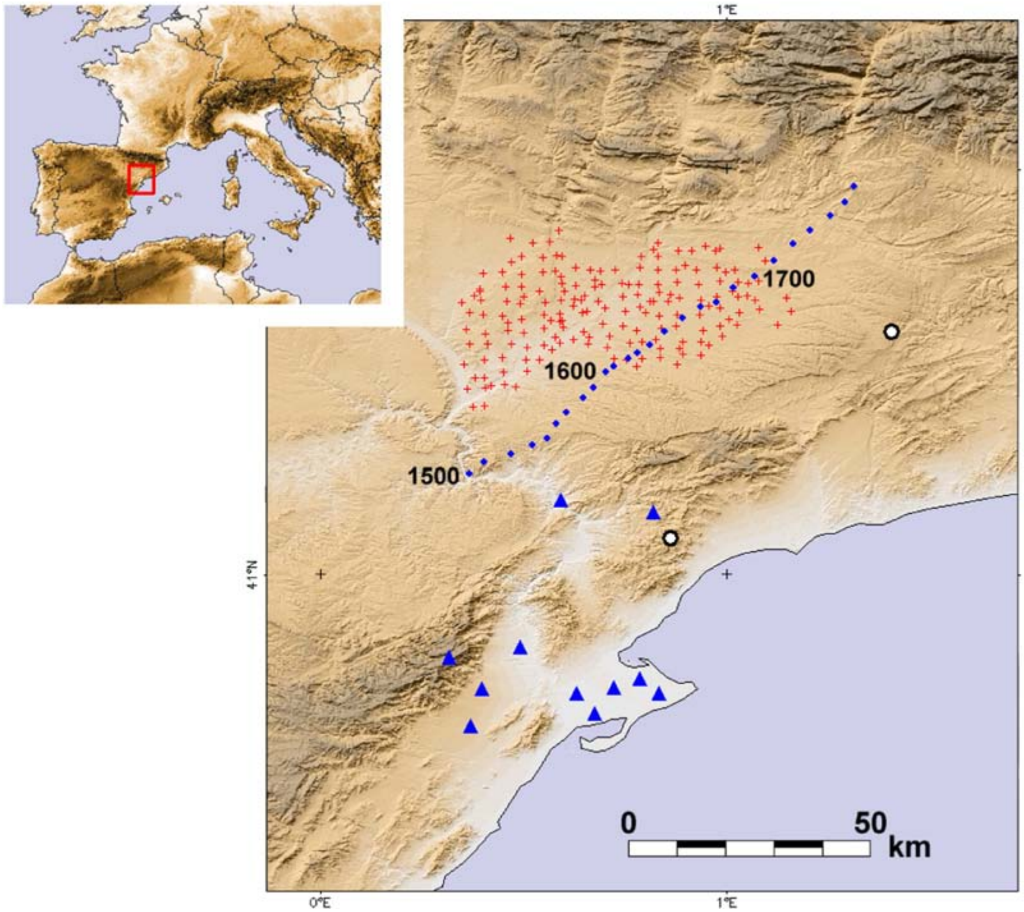

Fig. 1. Location of the area of study within Western Europe (upper left). The Lleida plain is the area covered by the hailpad network (red crosses). The Ebro river valley ends in a delta, a flat area where the majority of the Lightning Mapping Array (LMA) detectors are placed (blue triangles). The storm trajectory is represented by the radar cell centroids (blue dots) and the hours are indicative of the time of occurrence (UTC). Black and white circles correspond to the two C-Band radars covering the region of study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a large variability, making it difficult to use as a tool for predicting severe weather. On the contrary, IC activity may be a more robust indicator. The presence of abrupt increases in advance of the maximum flash rate of the storm and severe weather has been reported in many studies (Williams et al., 1999; Goodman et al., 2005; Wiens et al., 2005; Fehr et al., 2005; Steiger et al., 2007; Montanyà et al., 2009; Pineda et al., 2011). Williams et al. (1999) referred to these surges as lightning "jumps" and this feature has been used in algorithms to identify severe weather (Gatlin, 2006; Schultz et al., 2009; Gatlin and Goodman, 2010; Metzger and Nuss, 2013).

Besides this basic tripole structure (Williams, 1989, 2001), corresponding mainly to the convective updraft region, different charge configurations occur within other regions in the thunderstorm, including structures with more charge layers than the three of a standard tripole (Stolzenburg et al., 1998a; Tessendorf et al., 2007). Moreover, vertical charge structure opposite to usual has been reported (e.g. Marshall et al., 1995; Krehbiel et al., 2000; Rust and MacGorman, 2002; Rust et al., 2005; Wiens et al., 2005). The so called "inverted" charge structures are the opposite of the standard tripole, with a main midlevel region of positive charge, and negative charge regions above and below, and are conducive to producing +CG (Williams, 2001). Several hypotheses have been put forth to explain the cause of such an "inverted" charge structure. Although its origin is still uncertain, it may be related to the storm's microphysics; laboratory studies have shown that the local environment in which cloud and precipitation ice particles interact strongly influences the resulting polarity of the graupel charge (Saunders et al., 2004, 2006; Emersic and Saunders, 2010).

1.1. Predominantly positive CG (PPCG)

The mechanisms behind how some storms produce predominantly +CG lightning (PPCG), as opposed to the more commonly observed, are still not well understood. Observations in supercells indicate that they have a more complex charge structure than the basic normal tripole of common thunderstorms. Marshall et al. (1995) and Stolzenburg et al. (1998b) used data from several electric field balloons soundings of supercells to show that strong updrafts have a simpler charge structure than regions of downdraft or weak updraft. Strong updrafts present the typical 3 layer structure, while weak updrafts showed at least six charge layers, typically alternating polarity.

As reviewed by Williams (2001), several hypotheses have been put forth to explain the charge structure leading to +CG flashes and +CG-dominated thunderstorms.

1.1.1. Tilted dipole (Brook et al., 1982; Curran and Rust, 1992)

The upper positive charge region has been displaced laterally from the midlevel negative by a tilted updraft and strong upper level winds. Positive CG strokes would then result from the transfer of positive charge from the upper positive charge layer to the ground.

1.1.2. Precipitation unshielding (Carey and Rutledge, 1998)

Precipitation carries the negative charge out of the storm as it falls and "unshields" the upper positive charge layer, which would then be more capable of producing a ground stroke.