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[1] Two thunderstorms which developed in the northeastern region of Spain on 17 August 2004 are analyzed. According to radar and ground observations, one of these storms produced large hail (larger than 19 mm) and therefore could be severe. Both thunderstorms exhibited strong vertical developments with cloud tops reaching 17.5 and 14 km for the severe and the nonsevere ones, respectively. The total lightning activity was monitored, thanks to the Spanish magnetic-direction-finding and time-of-arrival (MDF/TOA) network and thanks to a regional very-high-frequency (VHF) interferometer network. Both storms presented low cloud-to-ground (CG) flash rates (lower than 2 min^{-1}) during their mature phase, while the intracloud (IC) flash rate reached 92 min^{-1} for the severe one. The IC/CG flash ratio was very high for both storms: 35 and 60 in average value for the severe and the nonsevere ones, respectively. The lightning characteristics exhibited low values in terms of peak current and multiplicity for negative CG (−CG) flashes and in terms of VHF source number per flash for IC flashes. The average multiplicity of the −CG flashes was 1.74 and 1.17 for the severe and the nonsevere storms, respectively, and their average peak current was −11.7 and −10.65 kA, respectively. When the presence of hail is suspected from high radar reflectivity values in both cells, the flash rates tended to substantially decrease. The severe storm produced positive CG (+CG) flashes during 1 hour, and at that moment, the multiplicity and peak currents of −CG flashes were very low. Lightning activity for both storms ended with a substantial increase of the −CG flash rate. The elevated charge hypothesis is consistent with the observations, especially if we consider two aspects of this hypothesis, the one about charge separation, which could be limited by the strong updrafts, and the one about the lightning initiation, which could be favored by low pressures at high altitude.

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1. Introduction

[2] Several works investigated the relationships between lightning activity and microphysics or dynamics in convective storms. For most of the thunderstorms following a typical behavior, the lightning activity starts with intracloud (IC) flashes after the ice phase develops in the cloud [*Williams et al.*, 1989; *Carey and Rutledge*, 1996]. The cloud-to-ground (CG) flashes occur when the main core of the convective cell descends to lower altitudes, and their rate peaks after that of IC flashes, when the rainfall is stronger and microburst occurs at the ground [*Goodman et al.*, 1988; *Williams et al.*, 1989; *MacGorman et al.*, 1989]. For these typical storms, the total lightning flash rate does not exceed generally 10 min^{-1}, the CG flash rate is lower than 2 min^{-1}, and the CG flashes are largely dominated by negative ones [*Williams et al.*, 1989; *Carey and Rutledge*, 1996]. In the severe storms, the lightning flash rate can be very high with values generally exceeding 30 min^{-1}, sometimes up to several hundreds min^{-1}, with low CG flash proportions and sometimes no CG at all during several-minute periods [*MacGorman et al.*, 1989; *Carey and Rutledge*, 1998; *Williams et al.*, 1999; *Lang et al.*, 2000; *Williams*, 2001; *Carey et al.*, 2003a, 2003b; *Wiens et al.*, 2005]. However, as indicated by *Williams* [2001] for example, a large variability is observed in the relationships between lightning activity and severe weather characteristics, especially tornadoes and large hail (diameter larger than 19 mm).

[3] On one hand, several observations of severe storms display dominant positive CG (+CG) flashes during the mature phase and for large periods (several tens of minutes) [*Reap and MacGorman*, 1989; *Branick and Doswell*, 1992; *Stolzenburg*, 1994; *Carey and Rutledge*, 1998; *Soula et al.*, 2004; *Wiens et al.*, 2005]. This +CG activity is remarkable insofar as its density is comparable to the negative CG (−CG) density generally observed below nonsevere storms. On the other hand, severe weather often occurs in the absence of clustered CG flash activity [*Williams*, 2001]. From a detailed analysis of severe storms in the contiguous

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United States, *Carey et al.* [2003a] reported a majority of severe storms (61%) associated with predominantly negative cloud-to-ground lightning. However, they pointed out a significant regional variability. Differences are also noted in the behavior of the lightning activity when high +CG flash proportions are observed. *Seimon* [1993], by analyzing a tornadic F5 supercell, observed a reversal in dominant CG polarity from positive to negative when the tornado touched down. However, this case is not a rule [*Carey et al.*, 2003a, 2003b]. On the contrary, by analyzing the activities of two simultaneous thundercells during the Mesoscale Alpine Program (MAP) experiment, *Soula et al.* [2004] observed a reversal from negative to positive polarity in the one which produced hail. A negative correlation between hail production and −CG flashes was observed in several studies [*Lang et al.*, 2000; *Knupp et al.*, 2003; *Soula et al.*, 2004]. In the case of a severe hailstorm with dominant +CG flashes (over 74%), *Carey and Rutledge* [1998] found also a negative correlation between temporal and spatial behavior of large hail and +CG flashes. *Lang and Rutledge* [2002] noted larger updraft volumes in the cases of thunderstorms with dominant +CG flashes. Several hypotheses have been reviewed by *Williams* [2001] to explain this dominant +CG activity.

[4] Recent studies show a tendency for total lightning activity to lead severe weather on the ground [*Williams et al.*, 1999], but high flash rates (> 30 min^{-1}) are no guarantee of severe weather [*Williams*, 2001]. A study of 32 severe storm cases by *Williams et al.* [1999] showed that an abrupt increase in the total flash rate systematically preceded the severe weather at the ground by 5 to 20 min. The total lightning activity and the radar-inferred precipitation structure of a severe hailstorm were investigated by *Carey and Rutledge* [1998]. This thunderstorm exhibited a very high IC-to-CG ratio after it became severe and produced large hail and weak tornadoes. The initial production of hail aloft corresponded very well with a rapid increase of the ratio IC/CG. In the study by *Lang et al.* [2000] devoted to two long-lived storms of Stratosphere-Troposphere Experiments: Radiation, Aerosols, and Ozone (STERAO-A), low −CG flash rates (<1 min^{-1}) and relatively high IC flash rates (>30 min^{-1}) were observed, and even long periods without any CG flashes (from 10 to 30 min) occurred. According to the authors of this study, the observations were consistent with the elevated charge hypothesis. This hypothesis proposed by *MacGorman et al.* [1989] supposes that the strong updrafts present in severe storms could lift the negative charge at higher altitudes in the thundercloud, which could favor IC flashes at the detriment of CG flashes. Furthermore, according to the authors, in strong updrafts, the particle could not spend enough time at a given level to acquire and separate charge, and therefore the charge density would be weaker. However, some observations were not clearly explained with this hypothesis, especially the low CG lightning flash rates during the thundercell collapse. In order to interpret the −CG and +CG flash activities during the whole lifetime of both storms, other mechanisms were suggested. For example, the wet growth for ice particles could limit the charging process of noninductive theory, but apparently, the observations could not validate it. The rainfall charge transport was also noted as a possible explanation, but once again, observations did not allow confirming it. During the Severe Thunderstorm Electrification and Precipitation Study (STEPS), the charge and cloud structures of several cases of severe storms were documented in the US area very favorable for dominant +CG storms [*Lang et al.*, 2004]. On one hand, results from this experiment infer the low CG rate with the lack of a lower charge center below the main charge at middle level of the cloud [*Wiens et al.*, 2005]. On the other hand, the production of dominant +CG flashes was explained by an inverted dipole structure [*Rust et al.*, 2005; *Wiens et al.*, 2005]. Recent modeling studies [*Mansell et al.*, 2005] confirm the role of the lower charge center for the production of strong electric fields required for initiating CG flashes. These results confirm also the possible presence of an inverted dipole with some noninductive charging schemes dependent on the graupel rime accretion rate.

[5] This paper presents a detailed study of two thunderstorms that occurred on August 17th of 2004 over the northeastern region of Spain which were hail-bearing cells. On this day, a trough of low pressure was located in the North Atlantic at the west of Ireland and organized a southwesterly flow on the Spanish Peninsula. A cold frontal system associated with a trough affected the studied region during this day; that is, low pressures appear at the surface during the crossing of the front. Frontal systems are not frequent in summer, but in contrast, when they turn up, they generate strong instability due to the contrast among existing warm air in front of the cool front and the cold air that arrives behind the frontal system. On this day, a temperature of −11°C was observed at 500hPa, the convective available potential energy (CAPE) value was 3308 J/kg, and 1369 CG flashes were recorded in the study area. The studied cells crossed the Catalan region, which is covered by a local network of total lightning detection, the national CG lightning location network, and three volumetric C-band radars. Observations made in both cases allow making a comparison with other works and a discussion about the mechanisms proposed to explain some characteristics of the lightning activity of hailstorms.

2. Data

[6] The CG lightning flash characteristics (time, location, polarity, peak current, and multiplicity) were obtained from the Spanish Lightning Detection Network (SLDN) composed of fifteen low-frequency (LF) combined magnetic-direction-finding and time-of-arrival (MDF/TOA) sensors over the Iberian Peninsula [*Rivas Soriano et al.*, 2005]. These sensors are of the same type as those of the National Lightning Detection Network (NLDN) in the USA. Additionally, the SLDN is supported by 10 sensors of the French Météorage network [*Tourte et al.*, 1988] and four sensors of the Rede de Descargas Eléctricas Atmosféricas network in Portugal [*Pérez Puebla*, 2004]. During the last 14 years, the network has been calibrated and evaluated several times [*Pérez Puebla*, 2004] following the same procedures applied to the NLDN [*Murphy et al.*, 2002; *Idone et al.*, 1993; *Mach et al.*, 1986]. The expected flash-detection efficiency for the SLDN is 90%, and its average location accuracy is 0.5 km [*Pérez Puebla*, 2004; *Rivas Soriano et al.*, 2005].

[7] Moreover, very high frequency (VHF) sources associated with the total lightning activity were provided by the Catalan Lightning Location Network (XDDE) operated by

the Meteorological Service of Catalonia (SMC) [*Montanyà et al.*, 2006]. This network covers the Catalan region (northeastern of Spain) and is composed of three VHF interferometers [*Richard and Lojou*, 1996]. Each interferometer detects the direction of the electromagnetic sources corresponding to leader phases of any lightning discharge. The combination of the three different directions provides two-dimensional location of the VHF sources, and therefore no three-dimensional location was available for this study. These interferometers operate in the VHF range from 110 to 118 MHz with 0.6 MHz of bandwidth. This network is able to locate a maximum of 100 detections per second with windows of 100-μs time resolution [*Soula and Chauzy*, 2001]. The identification of each source as isolated, beginning of flash, end of flash, or intermediate source is performed on the basis of spatial and temporal criteria [*Soula and Chauzy*, 2001]. These criteria for the XDDE are established so that two successive VHF sources are associated in the same flash if spatial and temporal intervals between them are lower than 7 km and 300 ms, respectively. The largest baseline between sensors is 135 km, and both thunderstorms studied in this analysis kept inside a range of 150 km from the center of the network. For this range, the detection efficiency for VHF sources of each sensor would be higher than 90% [*Richard*, 1998]. This network has been experimentally evaluated by means of electromagnetic field measurements and video recordings resulting in a flash detection efficiency of 93% with an average location accuracy of 0.5 km [*Montanyà et al.*, 2006].

[8] The three C-band radars from the SMC network provided volumetric reflectivity data for the region of study. These radars operate at long (240 km) and short (130 km) ranges, allowing Doppler filtering at the short range. Every 6 min, a series of 14 scans with elevations sweeping of 0.6° at the short range is made. We use in this work two kinds of display, vertical cross sections of volumetric data, and horizontal views of the maximum of the reflectivity in a given column (vertical projection). More details of the radar network are given in the study of *Bech et al.* [2004].

3. Analysis Method

[9] Two thunderstorms that developed inside the study area have been analyzed individually (Figure 1). Each thunderstorm main cell is primarily identified from the radar maximum reflectivity horizontal distribution plots and from the total lightning activity images. The 6-min frequency of the radar images allows a good monitoring of the lifecycle of the studied cells. The maximum reflectivity horizontal distributions and the vertical cross sections performed over the 6 min are used in the analysis. For the lightning activity, the locations of the strokes associated with the CG flashes are superimposed on the radar images.

[10] One of the interesting characteristics in some hailstorms is the presence of +CG activity. As indicated by many authors, positive CG flashes detected by the LF sensors can be misidentified as in-cloud lightning flashes [*Cummins et al.*, 1998; *Wacker and Orville*, 1999a, 1999b; *Orville and Huffines*, 2001; *Carey et al.*, 2003a, 2003b]. In order to have an accurate study, several positive flashes reported by the LF network are eliminated from the original data set. The criterion to validate a positive CG flash is based on a minimum threshold for the peak current value fixed at 10 kA because this value seems to well separate two groups of positive flashes within their distribution. For −CG flashes, no filtering is applied, even if the peak current values can seem low during some periods. Actually, these periods correspond to weak CG flash rates, what has been also observed by *Seity et al.* [2003]. *Cummins et al.* [2006], from a study made in Arizona, indicated that the low peak current −CG flashes (<10 kA) could be real CG flashes.

[11] For the representation of the total lightning issued from the XDDE system, all of VHF sources related to each flash are fitted into an ellipse by means of the least squares method in a linear regression. The large axis of the ellipse is oriented according to the main direction of the cluster of VHF sources included in the flash. In order to characterize the lightning activity, several rates are calculated with a 6-min resolution corresponding with that of the radar images. So the CG flash rate and the stroke rate for both polarities, the IC flash rate including the isolated VHF sources, are calculated with this time resolution.

[12] Although hail was reported from ground observations, the probability of hail (POH) has been calculated for both episodes. The criterion adopted for the POH calculation is based on radar observations and consists in exceeding a radar reflectivity value of 57 dBZ. This criterion agrees with the results from *Fraile et al.* [2001], who showed that high values reached by the radar reflectivity factor and the duration of the 45-dBZ detection are good variables for discriminating the occurrence of hail in thundercells. Moreover, in our cases, this threshold of 57 dBZ is in agreement with the method of *Auer* [1994] whatever the cloud top temperature is for the hail detection. From the maximum reflectivity horizontal distributions, cumulative areas where the reflectivity exceeds 57 dBZ and 40 dBZ [A(57) and A(40), respectively] are calculated. While A(57) corresponds to an indicator of probability of hail, A(40) is chosen to represent the convective region [*Steiner et al.*, 1995; *Parker and Johnson*, 2000]. Both cumulative areas are related in order to obtain the percentage of fractional areas A_{f} (57):

$$A_{\mathrm{f}}(57) = \frac{A(57)}{A(40)} \qquad (1)$$

The fractional area allows a comparison of the cells between them.

4. Case Studies

[13] Two different thunderstorms are studied. The main cell of the first thunderstorm (cell 1) produced hailstones up to 40 mm, exhibited high reflectivity levels, and +CG flashes. The main cell of the second thunderstorm (cell 2) also exhibited high reflectivity levels but no +CG activity. For this cell, no hail observations were available probably because it occurred in a region less populated than that of cell 1. Figure 1 displays both cell locations in the studied region at 1418 UT. Table 1 summarizes the main characteristics of both cells.

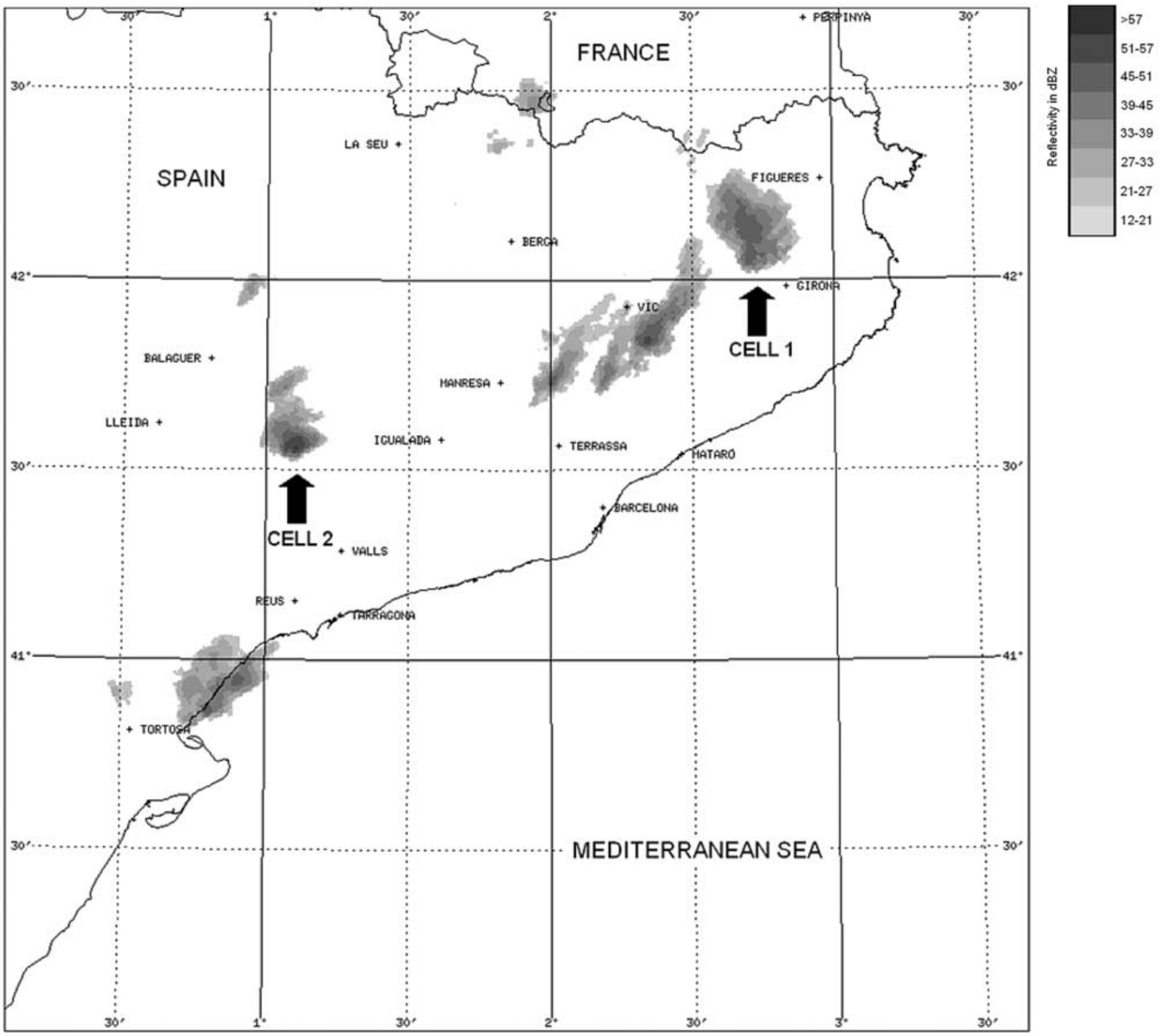

Figure 1. Location of the studied cells at 1418 UT in northeastern Spain.

4.1. Overview of Cell 1

[14] Cell 1 started inland at 1142 UT, moved northeastward to reach the Mediterranean Sea at 1500 UT, and progressed over the sea until around 1530 UT. Such a lifetime and several observations [(1) falls of big hailstones (>19 mm) were reported at 1248 UT, 1430 UT, and 1436 UT; (2) this cell was strongly vertically developed because the 35-dBZ echo tops reached an altitude of 13.75 km] reminds of a possible supercell. However, the available Doppler radar observations do not allow pointing out the presence of a mesocyclone to confirm the classification as a supercell. This cell produced 230 −CG flashes, 27 +CG flashes, and 9074 IC flashes including 1-VHF source events.

[15] Figure 2 displays the time series of the −CG and +CG flash rates, the −CG stroke rate, the IC flash rate, and the fractional area $A_f(57)$.The reflectivity exceeded 57 dBZ during two stages of the cell lifecycle. A third period with high reflectivity (>55 dBZ) was observed before the cell dissipation. The lightning activity and the thundercloud characteristics during these three periods and during the time interval between them are discussed in this section.

[16] The first period with very large reflectivity values started around 1224 UT, and $A_f(57)$ reached 0.31% at

Table 1. Characteristics of Both Studied Cells

	Cell 1	Cell 2
Cell Duration	3 hours 48 min	1 hour 30min
−CG Flashes	230	17
+CG Flashes	27	0
Average Multiplicity (Maximum)	1.74 (9)	1.17 (4)
IC Flashes	9074	1021
Average Peak Current for −CG (kA) (Median)	11.7 (9.65)	10.65 (9.10)
Maximum −CG Rate, min^{-1}	7.66	0.833
Maximum +CG Rate, min^{-1}	1	0
Maximum IC Rate, min^{-1}	92	34.1
Maximum $A_f(57)$, %	1.34	5.64
Maximum Cloud Top, km	17.5	14
60-dBZ Maximum Altitude, km	8.5	5.9
Isotherm, °C	−31	−13

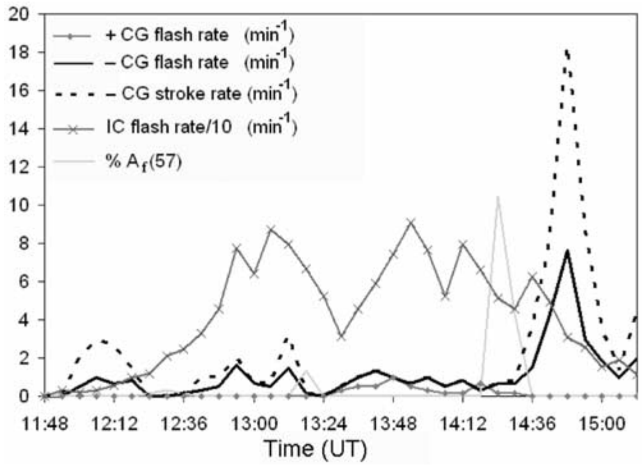

Figure 2. Time series of different lightning flash activities and fractional area $A_f(57)$ for cell 1.

1230 UT (Figure 2). The radar reflectivity cross section shows a core of high reflectivity reaching 60 dBZ at 5 km of altitude at that moment (Figure 3). Figures 3a, 4a, 5a, 6a, 7a, and 8a display a horizontal distribution of the maximum reflectivity factor detected in the cell with the lightning locations superimposed: ellipses fitted for including the VHF sources of each flash and symbols (white squares and crosses) for locating the CG flash strokes. Figures 3b, 4b, 5b, 6b, 7b, and 8b display a vertical cross section made according to the line drawn in Figures 3a, 4a, 5a, 6a, 7a, and 8a. Simultaneous to the increase of $A_f(57)$ at 1224 UT, the CG lightning activity stopped, and only the IC activity remained unaltered, even increased. Figure 4, which displays the cell at 1230, shows that the high reflectivity values quickly disappeared in the cell, probably with the fall of the hail at the ground, since the high values are close to the ground at that moment (Figure 4b). The second period was characterized by a core with reflectivity factor up to 60 dBZ at 1312 UT (Figure 5), and $A_f(57)$ reached 1.35% at 1318 UT. At 1312 UT, the core was located at an altitude of 8.5 km. Then at 1318 UT, the core fell to the echo bottom altitude (Figure 6) and disappeared at 1324 UT. For this 24-min period, both IC and CG activities drastically decreased, from 87 $\min^{-1}$ to 31.5 $\min^{-1}$ for IC flashes and from 1.5 $\min^{-1}$ to 0 $\min^{-1}$ for CG flashes. A large amount of IC flashes were 1-VHF source events (45% at 1324 UT). After 1324 UT the flash rates increased until around 1348 UT while the radar reflectivity was not very high in the cloud as indicated in Figure 7. The third period with large reflectivity values was around 1420 UT when the cell was still over land (Figure 8). A few minutes later, the −CG lightning activity considerably increased up to 7.6 $\min^{-1}$, while the IC lightning activity substantially decreased. However, the IC/CG ratio remained rather high (4 at 1448 UT). It is worthy to note that this ratio was very high during the whole lifetime of the thunderstorm, since it was always larger than 2.8. Actually, most of time, this ratio was larger than 19 (median value of 49). According to reports, for the first period of high reflectivity, hailstones of size more than 30 mm were observed at the surface, but there are no reports for the second one. In this case, hail precipitation could be in a noninhabited area. Bigger hailstones up to 40 mm were reported for the third period when the radar reflectivity was up to 55 dBZ.

[17] For more than one hour, +CG flashes were produced after the second period of large reflectivity values at 1324 UT. However, the +CG flashes did not dominate the CG lightning activity, which means that the present cell is not of the type of those which exhibit inverted dipole or tripole as described by *Wiens et al.* [2005] or *Rust et al.* [2005]. Figure 7 seems to indicate a tilted shape for radar reflectivity of the main cell of the system at that moment, which could correspond to the interpretation of the +CG production by *Curran and Rust* [1992]. However, the scattering and the location of the +CG flashes (Figure 7) do not confirm this interpretation. According to their location, these +CG flashes

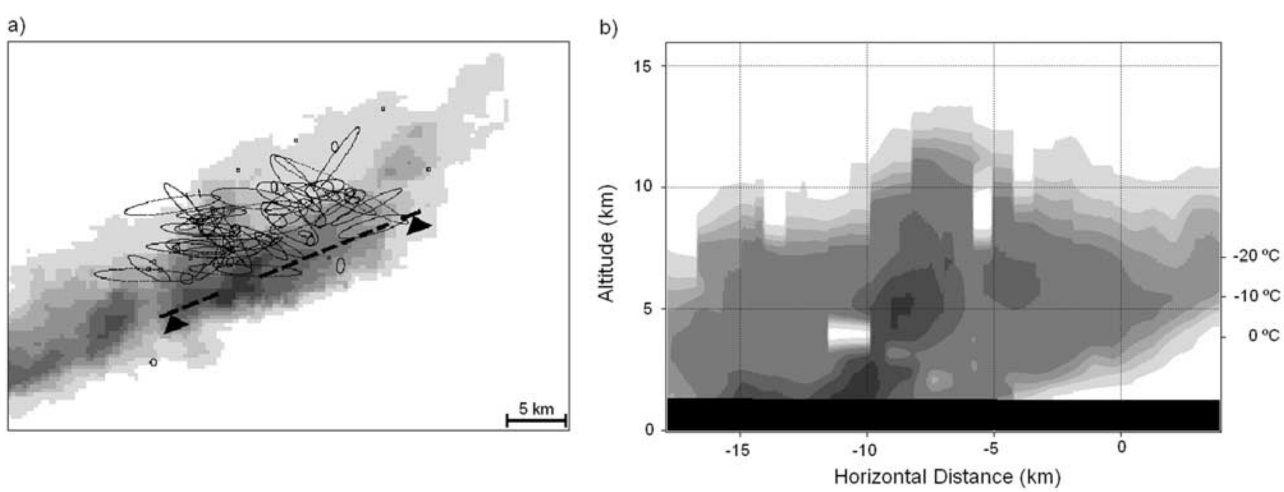

Figure 3. (a) Horizontal distribution of the maximum radar reflectivity for cell 1 at 1224 UT. The ellipses surround the VHF sources associated with some flash, the black squares indicate "singletons", white squares indicate −CG flashes, and white crosses indicate +CG flashes occurring between 1221 and 1227 UT. (b) Cross section of the radar reflectivity of cell 1 following the mark indicated in Figure 3a. Scale of reflectivity in Figure 1.

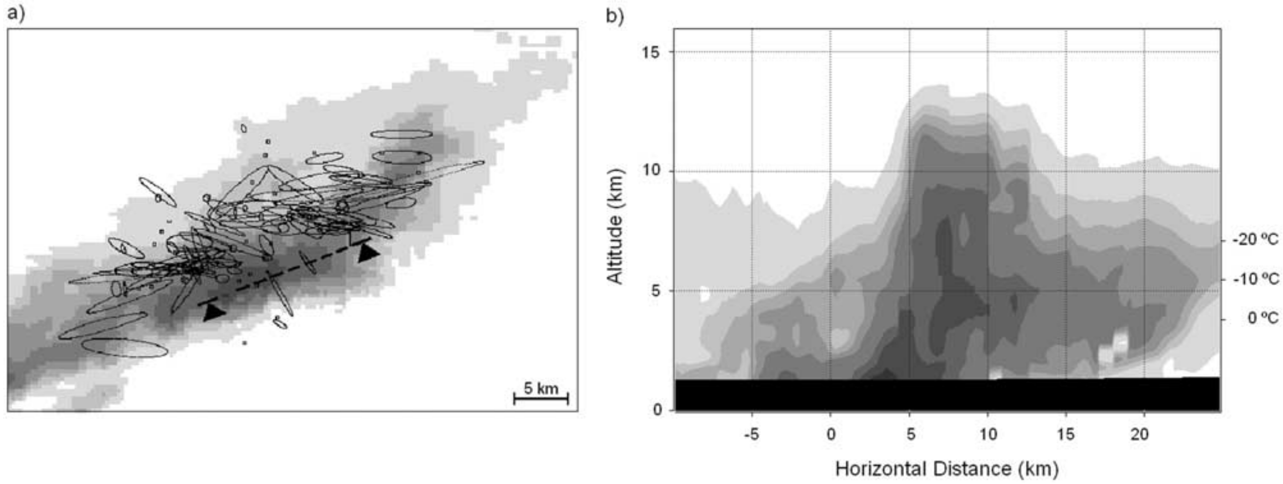

Figure 4. Same as Figure 3 at 1230 UT.

could be produced by enhancement of the lower positive charge as indicated by *Williams* [2001] or because of the typical evolution of the CG lightning activity for some convective systems. During this period, −CG flashes were characterized by strictly single return stroke, low rates (Figure 2), and low return stroke peak currents (Figure 9). As a matter of fact, peak currents for −CG flashes remained lower than 13.2 kA in absolute value (median value of 5.3 kA) between 1327 UT and 1432 UT, while for +CG flashes, they were much larger during the same period. After 1432 UT, −CG flashes recovered typical values for the peak currents (median value of −10.5 kA) and for the multiplicity.

[18] Available radar reflectivity cross sections denote a high vertical development of this cell with cloud tops up to 17.5 km at 1342 UT (Figures 3, 4, 5, 6, 7, and 8). Reflectivity cross sections reveal the presence of 50 dBZ at altitudes up to 11.25 km at 1424 UT.

4.2. Overview of Cell 2

[19] This cell, located 150 km southwest from the previous one (Figure 1), remained inland and produced lightning flashes from 1342 UT to 1512 UT. During this typical lifetime, high reflectivity values were observed as indicated in Table 1 and Figure 10. Cloud tops reached an altitude of 14 km. Only 17 −CG flashes and 1021 IC flashes (including 1-VHF source events) occurred, and no +CG flashes were produced.

[20] This cell exhibited two periods with strong radar reflectivity factors, during which $A_f(57)$ reached values higher than those observed for cell 1 (Figure 10). During the first period, around 1424 UT, $A_f(57)$ reached 6%, and during the second one (around 1448 UT), it reached 5.65%. During both periods, as observed in cell 1, the CG activity drastically decreased and disappeared. The maximum IC flash rate was 34 min^{-1} at 1436 UT and the IC/CG ratio was larger than 25 except during the last 1 min of the lifetime. The IC flash rate decreased also when high reflectivity was observed in the thundercell (Figure 10). During the dissipation stage, after 1448 UT, the −CG flash rate and the multiplicity reached their maximum values, 0.833 min^{-1} and 4, respectively. Therefore the −CG flash rate remained very low, and the multiplicity remained low during the whole lifetime. In the same way, the peak currents for −CG flashes were low during the whole lifetime, since the maximum value was −40 kA at 1500 UT. The highest

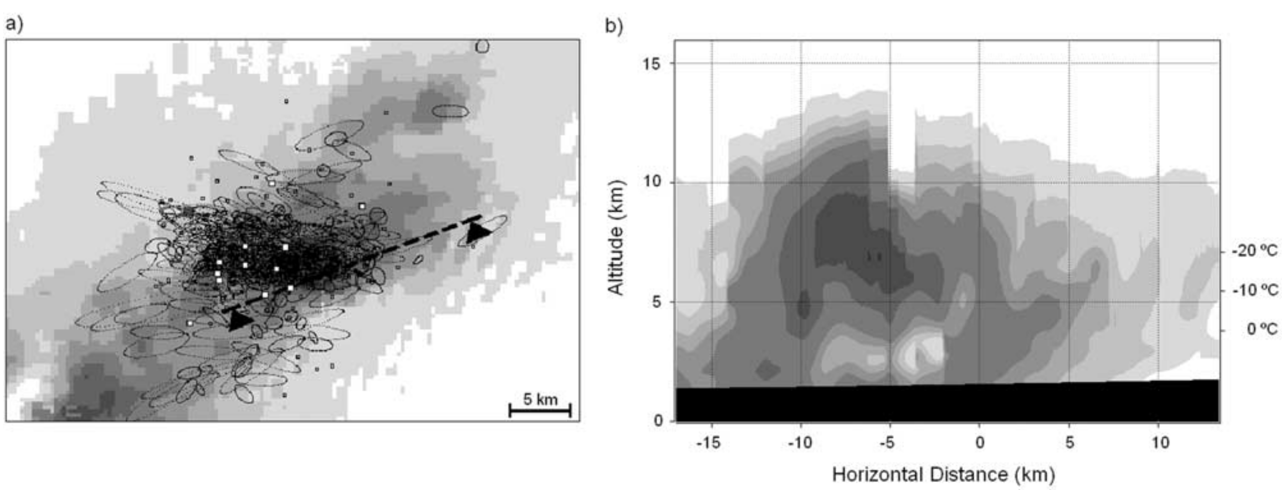

Figure 5. Same as Figure 3 at 1312 UT.

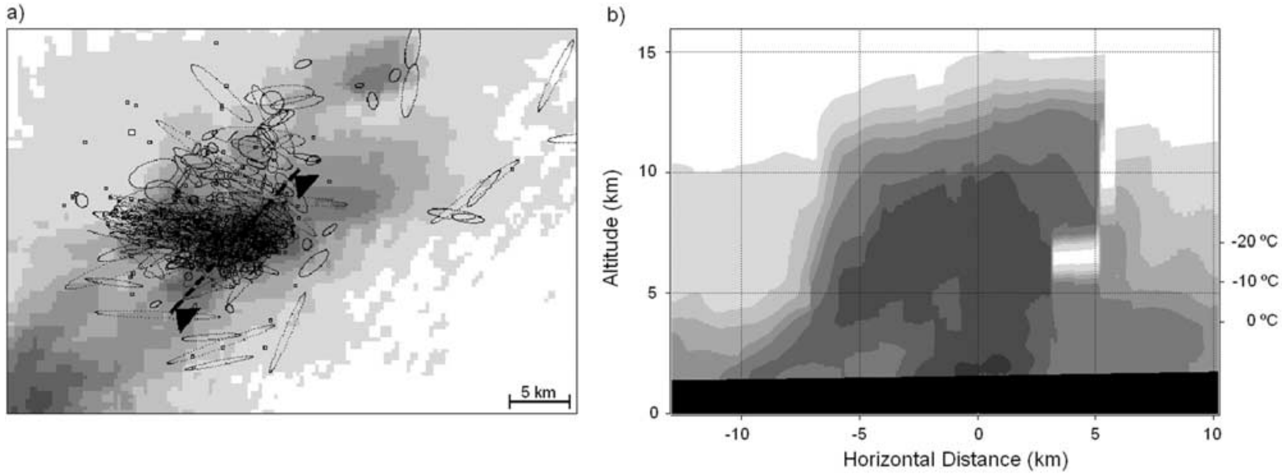

Figure 6. Same as Figure 3 at 1318 UT.

peak current values occurred during the dissipation period. Figure 11 displays consecutive cross sections in cell 2 between 1424 UT and 1448 UT. Even if no hail was reported by ground observations, probably because cell 2 was not located in an inhabited area, the previous reflectivity cross sections suggest a high POH. According to Figure 11a, the core of high reflectivity values reached a maximum altitude, around 6 km at 1424 UT, while it was at only 3 km during the second period.

5. Discussion

5.1. Lightning Flash Rates

[21] Both cells studied exhibited low CG rates during their whole lifetime. As a matter of fact, for cell 1, the CG flash rate remained lower than 2 min^{-1} during more than 2 hours and 30 minutes and exceeded this value in the last 30 minutes of its lifetime. For cell 2, the CG flash rate was much lower than 2 min^{-1} during the whole lifetime. Values of the CG flash rate larger than 2 min^{-1} produced by a thundercell have been reported in the literature. For example, *Carey and Rutledge* [1996] considered a thunderstorm observed with multiparameter radar and lightning detection systems. The CG flash rate of this storm reached about 5 min^{-1} and was at least 2 min^{-1} during about 30 minutes. *Soula et al.* [1998] noted a CG flash rate reaching 12 min^{-1}, with a very low proportion of +CG, in a case of storm producing a flash flood. A comparison of two cells performed by *Seity et al.* [2003] pointed out a CG flash rate with maximum values between 6 and 7 min^{-1} for a cell which did not produce hail. In this comparison, the second cell produced hail, and the CG flash rate decreased simultaneously with the detection of the hail by a multiparameter radar. *Williams et al.* [1999] studied the total lightning activity in several severe storms in Florida. The CG flash peak rates were variable, ranging from 1 to 22 min^{-1}, and in two cases of storm studied in detail, one without hail reported and the other classified as tornado, the CG flash rate peaked at 14 min^{-1} and 17 min^{-1}, respectively. On the other hand, several cases of severe storms characterized by hail displayed low values of CG flash rates during the whole lifetime [*Carey and Rutledge*, 1998; *Lang et al.*, 2000; *Soula et al.*, 2004]. In all cases of these hailstorms, the CG flash rate was lower than 2 or 3 min^{-1}. In terms of CG lightning activity, the

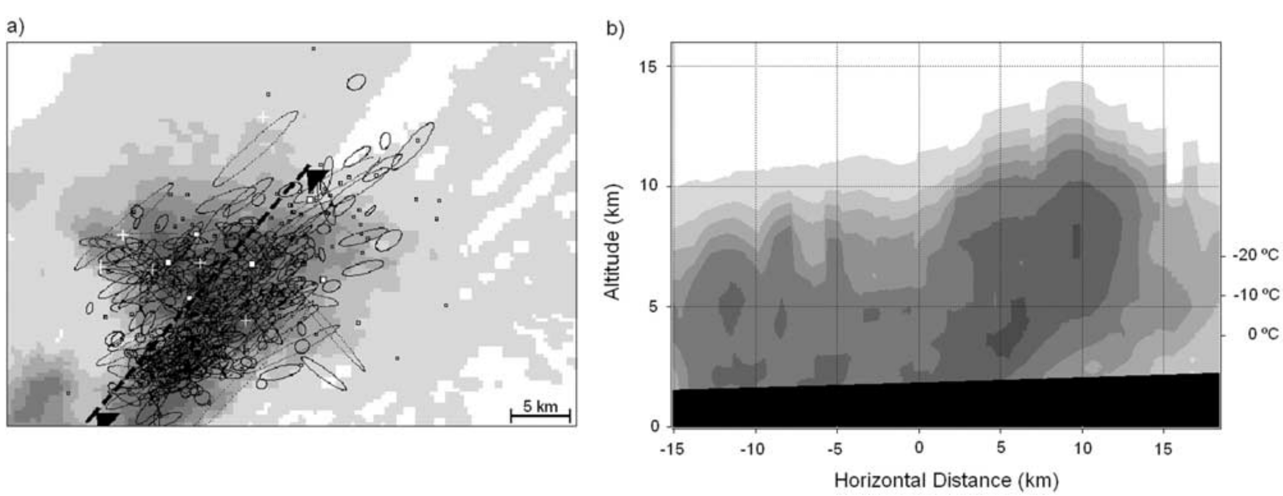

Figure 7. Same as Figure 3 at 1348 UT.

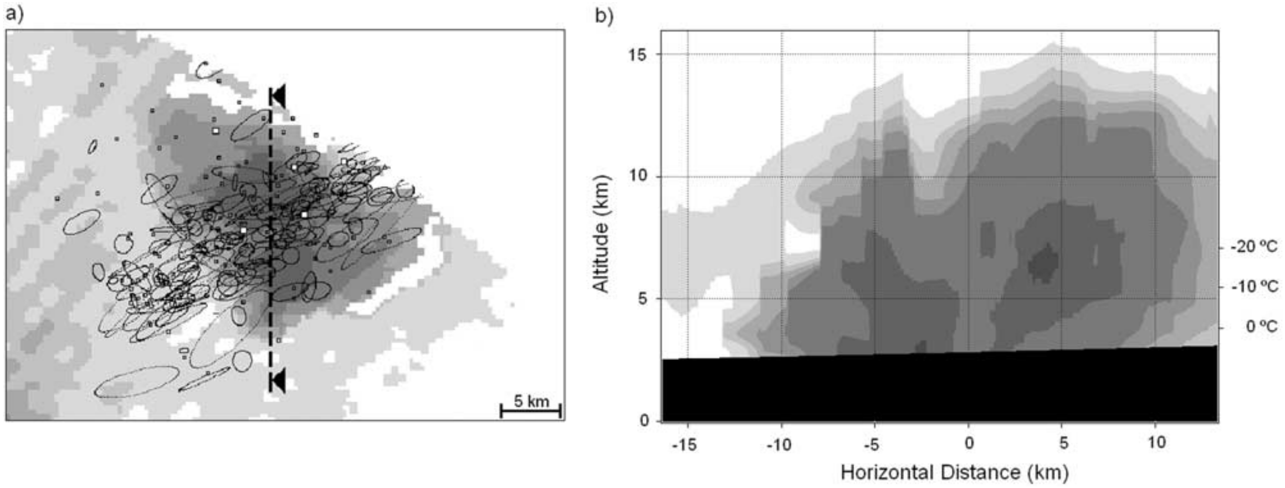

Figure 8. Same as Figure 3 at 1430 UT.

cells considered in this study confirm some observations made about hailstorms by other authors.

[22] In both cells, IC rates reached high values, 92 min^{-1} and 34 min^{-1} for cells 1 and 2, respectively. These values are not very large compared with the severe storms studied by *Williams et al.* [1999] or by *Wiens et al.* [2005]. However, in terms of radio source detection, all systems used are not comparable because of the time resolution and the storage capability. Williams et al. used a lightning detection and ranging (LDAR) system with specific criteria in order to build the lightning flashes, and Wiens et al. used a lightning mapping array (LMA) system with different criteria. During STERAO-A experiment, *Lang et al.* [2000] used the interferometric technique to map VHF emissions, and they found IC flash rates peaking at about 40 min^{-1} in two cases of intense convective storms producing hail and anomalously low negative CG flash rates. *Carey and Rutledge* [1998], who studied a severe hailstorm, found a maximum of about 40 min^{-1} during the period with available estimation of total lightning flash activity by using NLDN data and electrostatic field changes. In terms of lightning flash rates, the cells considered in the present study seem to be in the typical range for severe storms.

5.2. Lightning Flash Characteristics

[23] The observations for cell 1 are in agreement with *MacGorman* [1993], who reviewed earlier studies and suggested that many severe storms are characterized by high IC production and high percentages of +CG lightning. Only cell 1 produced +CG flashes during a continuous period of about 1 hour. In the observations by *Reap and MacGorman* [1989], *Branick and Doswell* [1992], *Stolzenburg* [1994], *Carey and Rutledge* [1998], and *Soula et al.* [2004], the positive CG flashes could be dominant during the mature phase of severe storms. In our case, cell 1 presented close values for both polarities. This observation can be compared with that in the case studied by *Lang et al.* [2000]; i.e., the thunderstorm of 12 July 1996, where both CG flash rates were comparable and low during the period with hail detected in the cloud. Some studies consider the characteristics of the different CG lightning flashes; i.e., the peak current and the multiplicity [i.e., *Carey and Rutledge*, 1998, 2003; *Carey et al.*, 2003a, 2003b] but fewer studies consider the total lightning activity.

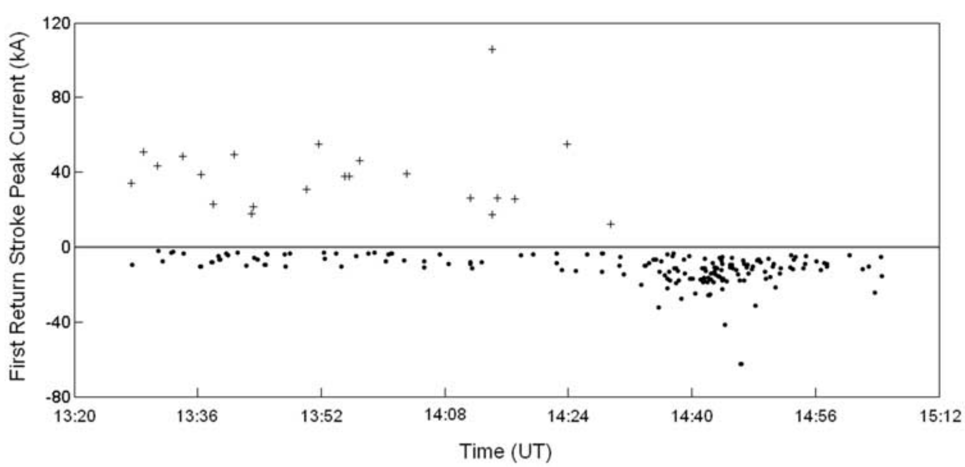

Figure 9. CG stroke peak currents for −CG (●) and +CG (+) flashes for cell 1.

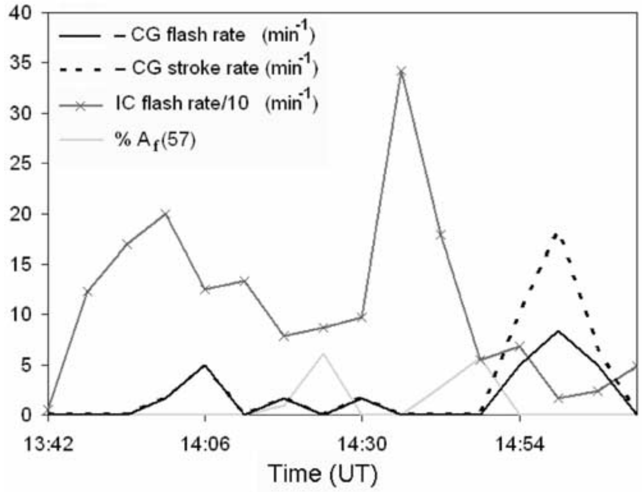

Figure 10. Same as Figure 2 for cell 2.

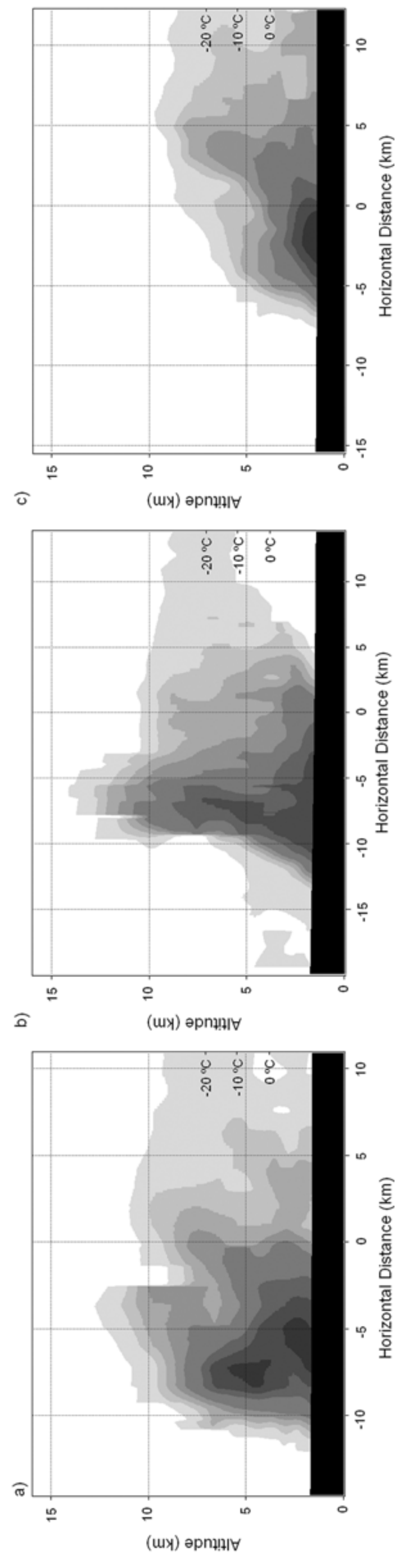

Figure 11. Radar cross section of cell 2 at (a) 1424 UT, (b) 1430 UT, and (c) 1448 UT.

[24] The average multiplicity for −CG flashes in cell 1 was 1.74, while the averaged peak current was −11.7 kA (median −9.65 kA). Cell 2 exhibited lower values: the average multiplicity for −CG flashes was 1.17, and the average peak current was −10.65 kA (median −9.10 kA). *Rivas Soriano et al.* [2005] found an average multiplicity of 2 and an average peak current of −27.3 kA (median −23.5 kA) for −CG flashes in the analysis of 10 years of CG flashes in the Iberian Peninsula. By analyzing 21 typical stormy days in the southwestern part of France, *Seity et al.* [2001] found average values of 2.39 (over sea) and 2.52 (over land) for the multiplicity and −32.1 kA (over sea) and −26.9 kA (over land) for the peak current. The values calculated in this study are therefore really low. Furthermore, during the period with +CG flashes produced by cell 1, i.e., between 1330 UT and 1430 UT, the multiplicity for −CG flashes was strictly 1 (Figure 2), and their peak current values were lower compared to other periods (Figure 9). This kind of observation was previously made by *Soula et al.* [2004], *Seity et al.* [2003], and *Carey and Rutledge* [2003]. It can indicate that less negative charge was available to be lowered to the ground. For cell 1, Figure 12 displays the time series of the proportions of IC flashes with only one VHF source; i.e., "singletons" according to *Williams et al.* [1999], and that of the IC flashes with more than 10 VHF sources. The singleton proportion continuously increased along the lifetime of the storm, even when the storm crossed the central zone of the area covered by the XDDE network. Given the values reached by this proportion, 50% during the period with large number of flashes and 58% at the end of the lifetime, a high proportion of IC flashes were therefore short events. On the other hand, the proportion of IC flashes with a large number of VHF sources decreased. In the study of severe storms in Florida by Williams et al., the proportion of singletons depended on the distance of the storm and could reach about 30% at large distances. We can suppose that a large proportion of the IC flashes did not neutralize large amounts of charge. As a matter of fact, the low number of VHF sources produced in a flash was probably due to a short propagation of the flash,

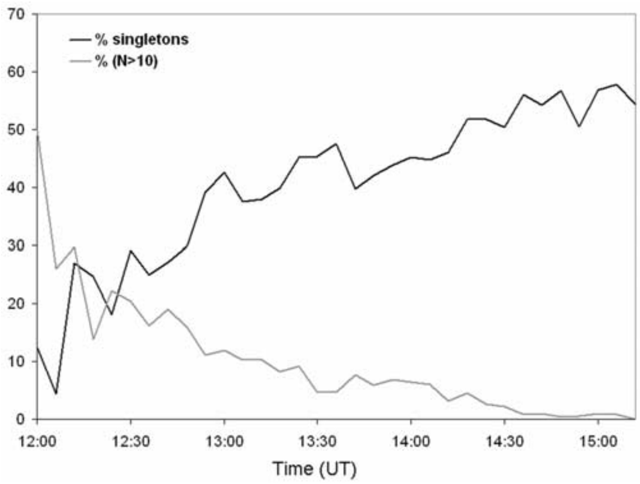

Figure 12. Time series of the proportion of "singletons" and IC flashes with more than 10 VHF sources for cell 1.

and therefore a small volume of charge was concerned by the discharge.

5.3. Cloud Structure

[25] The maximum cloud tops observed for both cells (17.5 and 14 km) are comparable to severe storms studied in detail by *Williams et al.* [1999] (16 to 18 km), *Carey and Rutledge* [1998] (12.5 km), or *Soula et al.* [2004] (15 km). Cell 1 exhibited reflectivity values larger than 60 dBZ, twice in its lifetime, simultaneous to a decrease of the CG flash rate. According to *Fraile et al.* [2001], the 60-dBZ value issued from a 5-cm radar can be considered a good indicator of a high POH. However, in the present case (cell 1), values larger than 60 dBZ did not persist for a long time and did not concern a large part of the cloud (Figure 2). Thus the behavior of cell 1 seems to correspond to that of hailstorms observed by *Seity et al.* [2003] and *Soula et al.* [2004]. The first large radar reflectivity values observed for cell 1 around 1224 UT were located at low altitude (Figure 3), and no CG flash was triggered at that moment. So these areas with large reflectivity values did not probably contain large amounts of charge. Later, around 1312 UT, cell 1 produced CG flashes, but at that moment, the larger reflectivity values were located at high altitude within the cloud (Figure 5). All flash rates were maximum at that moment, although the reflectivity values were lower than before. Around 1318 UT, the large reflectivity values were again large, exceeding 60 dBZ at low altitude and exceeding 55 dBZ within a very large proportion of the cloud (Figure 6). At that moment, both flash rates decreased very much and even down to zero for CG flashes, which clearly indicates that high flash rates and large reflectivity values did not exactly correspond in time (Figure 2). About 30 min later, the cloud system was more horizontally extended, and the reflectivity was much lower inside (Figure 7). The total flash rate increased, and scattered +CG flashes occurred in the apparently less convective area. The vertical cross section of Figure 7 indicates a tilted shape for the main cell. The possible origin of the +CG flashes at that moment can be the development of a small stratiform area or an enhanced lower positive charge [*Williams*, 2001]. Most of the IC flashes were located in the less vertically developed area of the cloud system. The last cross section made in cell 1 (Figure 8) shows again that no CG flash was triggered in the area with large reflectivity values at low altitude. On the contrary, CG flashes were triggered around a convective area, located in the north part of the system. After 1430 UT, the −CG flash rate and the multiplicity increased very much, but no radar cross section was available (Figure 2). The last period of lightning activity for cell 1, between 1430 UT and 1500 UT, was characterized by a strong increase of the −CG flash rate, up to 7.66 min^{-1}. Large values of the multiplicity were remarkable during this whole period, with a maximum stroke rate of 18 min^{-1} at 1442 UT (therefore an average multiplicity of 2.35) and a maximum multiplicity of 9. This period corresponded to a disappearance of the large reflectivity values in the cloud. Positive CG flashes occurred after the presence of reflectivity larger than 57 dBZ (up to 60 dBZ) at high altitudes (8.5 km), corresponding to the second period described in the overview of cell 1. Ground observations reported hailstones up to 40 mm during the +CG activity. Additionally, during this period of +CG activity, the IC flash rate reached its maximum.

[26] For cell 2, the cross section set available in Figure 11 shows also the presence of large reflectivity values at low altitude, while the CG flash rate was very low. No CG flash was detected during the 6-min period around 1424 UT when the reflectivity structure presented two cores, including one at low altitude. The IC flash rate decreased also significantly when the large reflectivity was observed within the cloud. The −CG flash rate increased at the end of the lifetime of the thundercell, but it remained relatively low with a maximum of 0.833 min^{-1}. The multiplicity exhibited an average slightly larger than 2 and a maximum value of 4 at 1500 UT.

5.4. The Elevated Charge Hypothesis

[27] During both storm collapses, the IC rate was low and progressively decreased, while the −CG activity peaked. Several studies of thunderstorms pointed out a typical behavior [*Goodman et al.*, 1988; *Williams et al.*, 1989]. *MacGorman et al.* [1989] found that the CG flash rate peaked after that of IC flashes, when the rainfall and the dynamical phenomena were stronger at the ground. However, we note in the present study that the IC and CG flash rates could simultaneously increase and decrease during the cell lifetime. For example, when large reflectivity values were observed at low altitudes, both flash rates decreased. The hypothesis of the elevated charge was proposed by MacGorman et al. to explain the large proportion of IC flashes in the cases of storms with strong updrafts. According to this hypothesis, two factors could contribute to favor the IC flashes over the CG ones: the reduced electric field between the negative charge center and the ground, and a lower distance between both positive and negative charge centers to trigger IC flashes. Other consequences of the strong updrafts were proposed, especially the limited time for particles to grow and acquire charge at a given level. *Lang et al.* [2000] discussed this hypothesis after analyzing data about severe storms and noted that this hypothesis was not relevant to the whole set of their observations. In particular, this hypothesis could not explain the low rates of CG flash they observed even during the collapse of their

convective cells. In our case, all observations could be consistent with the elevated charge hypothesis. As a matter of fact, the IC flash proportion was always high during the mature phase of the storm; the characteristics of the lightning flashes indicated little negative charge available for CG discharge, a large proportion of short IC discharges, and finally an increase of the CG flashes at the end of the storm lifetime. As described by previous authors, the elevated charge hypothesis can explain the large proportion of IC flashes. Assuming the high flash rates observed and the low VHF sources number per flash, we can think that the conditions of discharge initiation were favorable in such a configuration. The strong altitude and therefore the low pressure corresponding to the charged regions of the cloud in the scheme of the elevated charge could favor the flash production by lowering the electric field threshold.

6. Conclusion

[28] An analysis of the total lightning activity in two hail-bearing thunderstorms has been done. It is performed with data from volumetric radar scans, from MDF/TOA sensors network for CG lightning flashes, and from a VHF interferometric system for total lightning detection. The different rates of lightning flash and the flash characteristics have been calculated over 6-min periods. The most important results are summarized in the following:

[29] 1. Both cells produced CG flash rates lower than 2 min^{-1} during their mature phase. These storms could be classified in the group of severe storms characterized by low CG flash rates.

[30] 2. Both cells presented high IC rates (with maximum values of 92 min^{-1} and 34 min^{-1} for cells 1 and 2, respectively) and very high IC/CG ratio, about 49 for the median value for both cells. These values are typical for severe storms, but differences in the detection technique and network capabilities make direct comparisons difficult.

[31] 3. Only cell 1 produced +CG flashes. During the presence of +CG activity, −CG return stroke peak currents and flash multiplicity were low. In the same way, the average peak currents and the multiplicities observed during the whole lifetime of both cells were lower than the typical values. It suggests that, in both storms, less negative charge was available to be lowered to the ground, probably because of strong updrafts. The presence of +CG flashes in cell 1 could be due to a prior stronger updraft and the development of a small stratiform area or to an enhanced lower positive charge.

[32] 4. Both cell lifetimes ended with an enhancement of the −CG flash rate and a decrease of IC flash rate.

[33] 5. The high radar reflectivity values (>57 dBZ) are used for estimating the probability of the presence of hail. When such values are observed in both cells, the flash rates tend to substantially decrease.

[34] 6. The high IC/CG ratios observed are consistent with the elevated charge hypothesis. Furthermore, the large amount of singletons in the IC flashes, corresponding with the strong vertical development of the cloud, suggests that the charged regions reside in elevated regions where flashes could be more easily initiated in conditions of low pressure. As a matter of fact, the breakdown electric field threshold decreases with altitude.

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