Differences between visible characteristics of lightning flashes for a case study occurred in southeast Brazil during the summer of 2012/2013

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ABSTRACT: The objective of the present work is to analyze one thunderstorm day that produced lightning with peculiar characteristics, different from those commonly found in other works on the literature. The data was obtained by the RAMMER network, composed by four high-speed cameras, during the summer of 2012/2013 in the city of São José dos Campos, Brazil. The relatively large number of high-speed cameras has enabled us to record a statistically significant amount of negative cloud-to-ground lightning flashes per thunderstorm day. We chose as control-cases the five days that had the highest amount of lightning recorded by the cameras, making a total of 361 flashes. The analysis was performed in two ways, the first one considering the control-cases and the second one considering only the case study. After analyzing all lightning data we found that the geometric mean of the flash duration was 270 ms, the average multiplicity was 4.3 and the percentage of single strokes was 20.8% (75 events). These values are similar to those found in previous single-station studies for the same region. The case study of this work is February 22nd, 2013, which had a sample size of 55 negative cloud-to-ground lightning. The visible lightning characteristics for this day were: a) flash duration geometric mean of 193 ms; b) an average multiplicity of 2.8; and c) a percentage of single stroke flashes, around 36.4% (20). Also, an evaluation of the sample obtained on that day was performed using lightning location system BrasilDAT. After the evaluation of the statistical tests, we point out the following three hypotheses which will be addressed in the work: a) synoptic condition of the day: the weather phenomenon acting in the region during that day may have favored the formation of clouds with smaller vertical development, thus leading to temporally shorter and single-stroke flashes; b) region of occurrence of lightning: the topography can influence the formation of clouds in order to create the necessary conditions for the occurrence of anomalous features; and c) observation period: it is possible that the flashes have been observed during the initial phase of the development of the thunder clouds, which would be directly related to observed characteristics. Satellite and radar images will also be used as complementarily tools for the analysis, which is currently under development.

INTRODUCTION

The use of high-speed camera to study lightning began in the 90s. Early studies using that tool were performed by Mazur et al. [1995], Mazur et al. [1998], Ballarotti [2005], Saba et al. [2006] and Campos et al. [2007]. The analysis of lightning flashes through the high-speed camera allows some features to be determined more precisely, such as, flash multiplicity and duration, continuing current times, interstroke intervals, presence of forked strokes within a flash, among others.

Antunes et al [2013], Antunes et al [2014] and Antunes [2014] did a study on the multiplicity, flash duration and interstroke intervals of 361 negative cloud-to-ground lightning, recorded by a network of high-speed cameras. This study aimed to observe thunderstorms from different angles; the camera network is called RAMMER (Portuguese acronym for Automated Multi-camera Network for Monitoring and Study of Lightning) [Saraiva et al., 2011, 2012]. The observations were made during the summer of 2012/2013 in the city of São José dos Campos and nearby region. The RAMMER network used four sensors strategically placed to cover the area of interest. Among the registered thunderstorm days during the campaign, five days were chosen due to the greatest number of negative cloud-to-ground lightning flashes (CG) filmed by the cameras.

The results found by the author were: average multiplicity of 4.3, geometric mean of flash duration of 270.2 ms and percentage of single stroke flashes of 20.7% (75 events). Previous studies for the same region found similar values: average multiplicity between 3.8 and 4.6, geometric mean of flash duration between 163 ms and 300 ms and percentage of single stroke flash between 17% and 20% [Saba et al., 2006; Saraiva et al., 2010; Ballarotti et al, 2012]. When the analysis was performed for each thunderstorm day, one particular day presented some different results. February 22nd had 55 negative CG flashes recorded by cameras of the RAMMER network with an average multiplicity of only 2.8, geometric mean of flash duration 193.1 ms and percentage of single stroke flashes of 36.4% (20).

Due to the fact that the sample size of that day is not so large when compared to all flashes recorded (361), we applied the Monte Carlo resampling method to verify the influence of the sample size on the differences in the lightning characteristics found. As the distribution of the original population is known, the method consists of several random samples from that population. The result is obtained by statistical parameters such as mean, standard deviation, standard error and so on.

Saraiva [2010], Saraiva et al. 2011, Antunes et al [2014] and Antunes 2014 showed that there is a linear increasing relationship between the reflectivity of the clouds, provided by weather radar, the multiplicity and flash duration of negative CG flashes.

Lund et al. [2009] have made a study of the reflectivity of the thunderstorm clouds where they found that most of negative CG flashes started in convective cloud regions that were within the 35 dBZ regions.

Based on the above information the present study used the MapInfo software (which provides georeferenced database containing information of latitude and longitude) to correlate data from high-speed cameras, local lightning location system (LLS) BrasilDAT [Nacarrato et al. 2012] and weather radar to try to find physical and meteorological explanations for the low values of multiplicity and flash duration of lightning that occurred on February 22nd of 2013.

DATASET

The data used in this work was obtained by the RAMMER network, composed by four high-speed cameras, during the summer of 2012/2013 in the city of São José dos Campos, Brazil. The estimated recording range of each camera is about 60 km. The relatively large number of high-speed cameras has enabled us to record a statistically significant amount of negative cloud-to-ground lightning flashes per thunderstorm day over that region. We chose as control-cases the total dataset of the five days that had the highest amount of lightning recorded by the cameras, making a total of 361 flashes.

The camera model used was the Phantom v9.1, set to record videos at 2500 frames per second (fps). Each of the cameras had a GPS synchronizing each frame recorded with a precision of 1 ns, enabling the correlation of flashes recorded by the cameras with to the local LLS.

The local LLS BrasilDAT currently consists of 56 EarthNetworks Lightning Sensors (ENLS). Each one of them has a timing circuit based on GPS, a digital signal processor, internal storage and communications equipment to the Internet. The ENLS is a broadband system with detection frequency ranging from 1 Hz to 12 MHz and uses a TOA (Time-Of-Arrival) method to triangulate the ground strike point position and time of occurrence of the return strokes while it is also able to provide additional information, such as the peak current of the discharge.

The location of flashes was correlated with reflectivity data of the nearby weather radar. CAPPI (Constant Altitude Plan Position Indicator) obtained at 5 km height was used. It is a way to visualize horizontal slices of the clouds in the form of reflectivity data (given in dBZ). Data from multiple scans at multiple elevation angles of the radar are combined to form a horizontal plane of the reflectivity (dBZ).

Figure 1 show the location of the weather radar used in this work, radar scans cover an area with a radius of 250 km that involves the region where the lightning flashes were filmed.

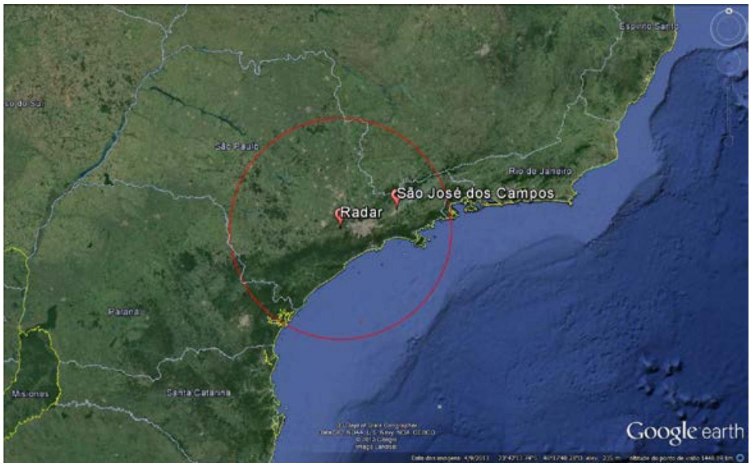

Figure 1 - The red circle represents the field of view of the radar of the São Roque city.
Source: Google Earth [2014].

The study by Lund et al. [2009] show that most lightning flashes start in the convective regions of the cloud within the areas of 35 dBZ between two bands of altitude, 3-6 km and 7-10 km. The level of reflectivity 35 dBZ is commonly associated with strong convection within the cloud. The echoes are derived of the particle with size of millimeters in diameter [Macgorman and Rust, 1998; Takahashi et al., 1998]. Theories of electrification indicate that around -15ºC particles like graupel, hail and ice crystals with negative charges are located. According to the basic structure of the electrical storm cloud [e.g., Krehbiel, 1986; Williams, 1989, Rakov and Uman, 2003], the main negative charge center is concentrated in the region of temperatures around -10°C and -15°C [Williams, 1989]. Therefore, the height of 5 km (equivalent to those temperatures) was chosen when acquiring the CAPPI images.

ANALYSIS AND RESULTS

Antunes et al. [2013], Antunes et al. [2014] and Antunes [2014] conducted a study on the characteristics of the negative CG flashes that were registered with a network of high-speed cameras (RAMMER). The relatively large number of high-speed cameras has enabled us to record a statistically significant amount of negative cloud-to-ground lightning flashes per thunderstorm day. We chose as control-cases the five days that had the highest amount of lightning recorded by the cameras, making a total of 361 flashes.

When the analysis was performed using all lightning flashes, the results for the multiplicity (4.3) and flash duration (270.2 ms) were similar to the results found by other authors who studied these lightning characteristics in the same region [Saba et al. 2006; Saraiva et al. 2010; Ballarotti et al. 2012]. However, when the analysis was performed separating the data per thunderstorm day, February 22nd showed values considerably different from what is commonly observed. The average multiplicity found was 2.8, the geometric mean of flash duration 193.1 ms and 36.4% of the flashes had only one return stroke.

The Monte Carlo method was used to resample the original amount of 361 recorded flashes in subsamples of 55 flashes, 1,000 times, and those characteristics (flash multiplicity and duration) were recalculated for each resample. The method reproduced the distribution of flash multiplicity only 3 times among the 1,000 (0.3%). This amount is very low, so the distribution is considered an anomaly. However, when the Monte Carlo resampling method was applied for the flash duration dataset the distribution was reproduced 161 times (16.1%). Even though this value may be considered low, it is not an anomaly.

In order to try to find physical and meteorological explanations for these abnormal values found in the multiplicity and flash durations on February 22nd, satellite images of clouds were analyzed. Figure 2 shows the sequence of images provided by the GOES 13 satellite. The images are for the period in which the flashes were recorded, and the green circle indicates the region where the observations were made with arrows indicating the thunderstorm cell where the flashes occurred.

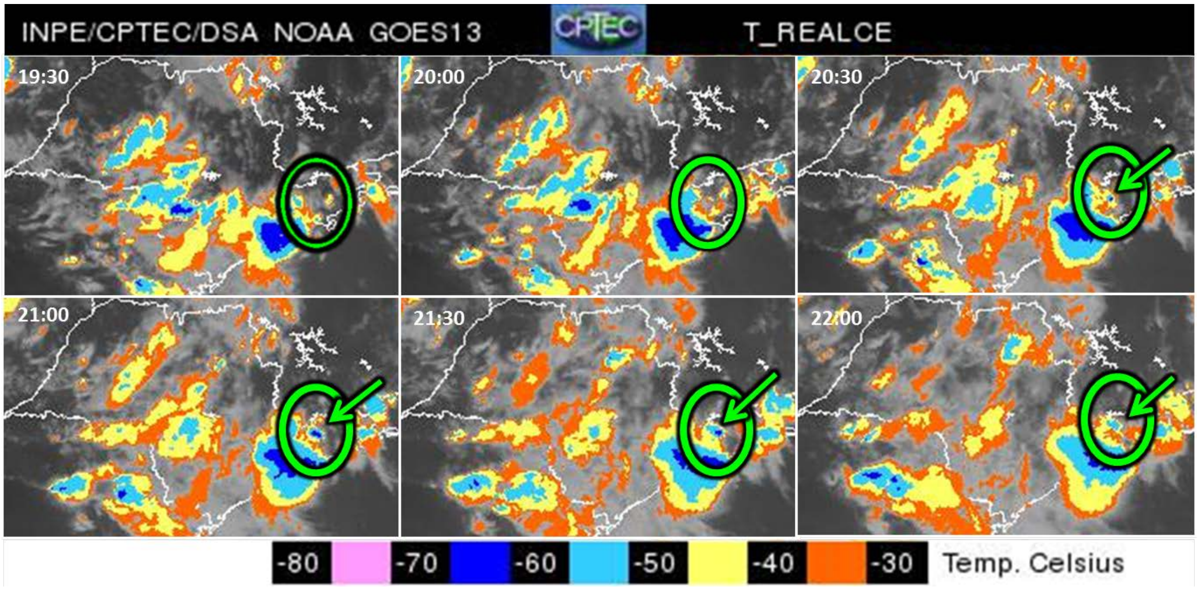

Figure 2 - Satellite images provided by GOES13 infrared channel on February 22nd of 2013. Times of the satellite image are given in UT.

Source: http://satelite.cptec.inpe.br

One can notice that the storm cell where the flashes were filmed is quite small compared to the system around it and remains isolated from other cells throughout the period of observation. Also, in order to analyze the structure of this thunderstorm cell, data from the nearby weather radar and local LLS were also used. The radar provides data with time intervals of 15 minutes, and due to this feature, the LLS data were also separated at intervals of 15 minutes so they could be correlated.

Considering that the region of negative charge of the cloud is related to the contours of 35 dBZ at -15°C (5 km height), one can infer that the initiation of negative CG flashes occurs within this region. The images generated by MapInfo were then used to study thunderstorm cells that gave rise to the flashes.

Figure 3 shows the reflectivity of thunderstorm cloud with 15-minute intervals during the period in which the flashes were recorded. The white dots indicate the location of each flash. The four red dots indicate the location of the high-speed camera network RAMMER. Green ovals indicate the region of the cloud where the lightning recorded by cameras occurred. The figure does not show the image for 21:45 UT because during this time interval no flashes were recorded by the camera.

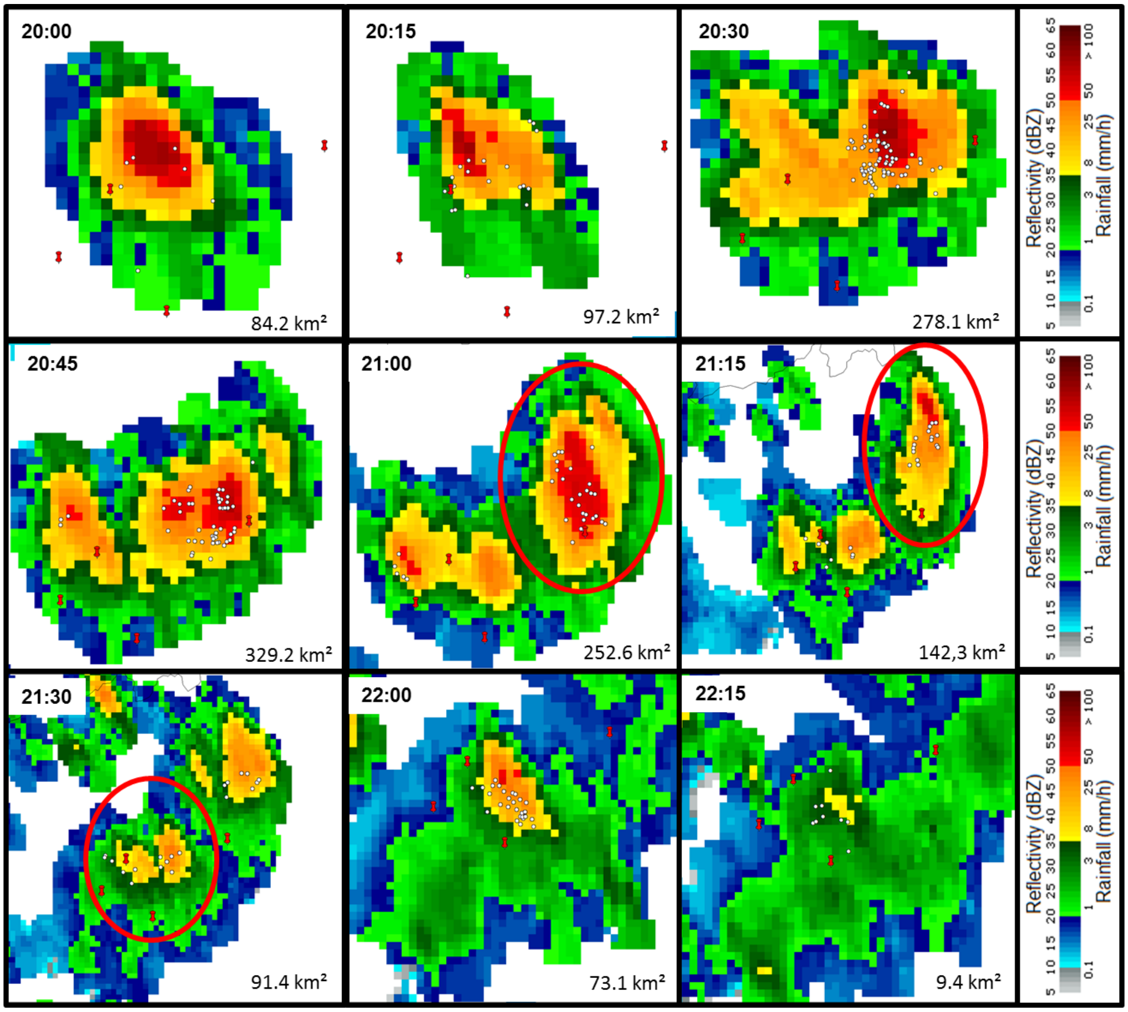

Figure 3 - CAPPI at 5 km height of the thunderstorm cloud reflectivity during the observation of flashes

By looking at the images it was possible to estimate that more than 90% of flashes occurred within the contour of reflectivity from 35 dBZ. Other papers in the literature also showed the same result for this reflectivity level [Lund et al., 2009; Saraiva, 2010; Saraiva et al 2011].

Saraiva [2010], Saraiva et al 2011, Antunes [2014] and Antunes et al [2014] found a relationship between the size of the area of 35 dBZ, the multiplicity and duration of lightning flashes. These works showed that there is a linear correlation between these parameters relative to the growth of the contour of 35 dBZ limited to areas between 300 and 400 km ^{2}. It is speculated that this limit is a consequence of the fact that above this size the convective cell is no longer isolated and tends to merge with neighboring cells. That would cause the exchange of mass and electric charges between them, making it impossible to estimate the exact size of the negative charge region. The sequence of images in Figure 3 also shows that the thunderstorm cell remained isolated until 21:00 UT, and after this time the cell began to mix with its neighboring cells.

In order to study the relationship between the convective region of the cell and the charactersitics of the associated lightning flashes, the size of the area with 35 dBZ reflectivity was calculated for each time and then compared with the multiplicity and total duration of the recorded lightning flashes, as shown in Table 1.

Table 1 – Temporal evolution of the35 dBZ contour, and flash multiplicity and total duration.

Hora	Area (km²)	Multiplicity	Flash Duration (ms)
20:00	84.2	3.3	208.27
20:15	97.2	3.6	250.76
20:30	278.1	3.0	138.83
20:45	329.2	3.5	300.8
21:00	252.5	3.3	173.69
21:15	142.3	4.0	275.72
21:30	91.6	1.6	100.9
22:00	73.1	1.4	84.31
22:15	9.4	2.6	164.13

Analyzing the reflectivity of the thunderstorm cell we can see that from 20:00 UT until 20:30 UT the cloud was in its developing stage. At 20:45 UT it reached maturity and at 21:00 UT its dissipation stage started. These stages were reflected on the amount of flashes recorded in each period. Table 2 shows all flashes recorded by the cameras during each period and their respective multiplicity on 02/22. It is possible to note that the amount of flashes in each time interval varies while the average multiplicity, however, remains approximately constant until 20:45. Unfortunately, between 21:00 and 21:15 UT the cameras recorded a particularly small number of cases, which makes the average of the flash parameters not as reliable. From of 21:30 UT mixing cells took place and, at 22:15, the convective region (35 dBZ) starts to decrease. Table 2 shows that from that time on the average multiplicity also begins to decrease. The number of cases for each time period was not enough to have a statistically significant sample, so the maximum multiplicity of each period was also analyzed. Between 20:00 UT and 20:15 UT the maximum multiplicity was 6; between 20:30 UT and 20:45 UT the maximum multiplicity increases for 10 and then after that time the maximum multiplicity of each period is decreasing.

Table 2 - Multiplicity of negative cloud-to-ground lightning flashes separate in 15-minute intervals.

HORA	MULTIPLICITY											MEAN
20:00	1	6	6	3	2	2						3.3
20:15	3	1	2	4	3	6	6					3.6
20:30	1	3	2	2	8	1	1	10	1	1	3	3.0
20:45	4	2	10	2	1	2	1	6				3.5
21:00	4	5	1									3.3
21:15	6	1	5									4.0
21:30	4	1	1	1	1							1.6
22:00	1	2	2	2	1	1	1	1				1.4
22:15	3	3	2									2.6

Figure 4 shows a scatter plot of the durations of the lightning flashes as a function of their multiplicities. The duration of the lightning tends to increase with the increase of multiplicity. It is estimated that propagation of the leader inside the cloud is directly related to the flash duration. According to the bidirectional leader model, while the stepped leader of the first return stroke develops toward the ground, the positive portion of the bidirectional leader also develops inside the cloud. Through observations of lightning in the VHF band, it was identified that the propagation of the leader within the cloud occurs predominantly in a horizontal way [Shao et al., 1995; Mazur, 2002, Lund et al., 2009].

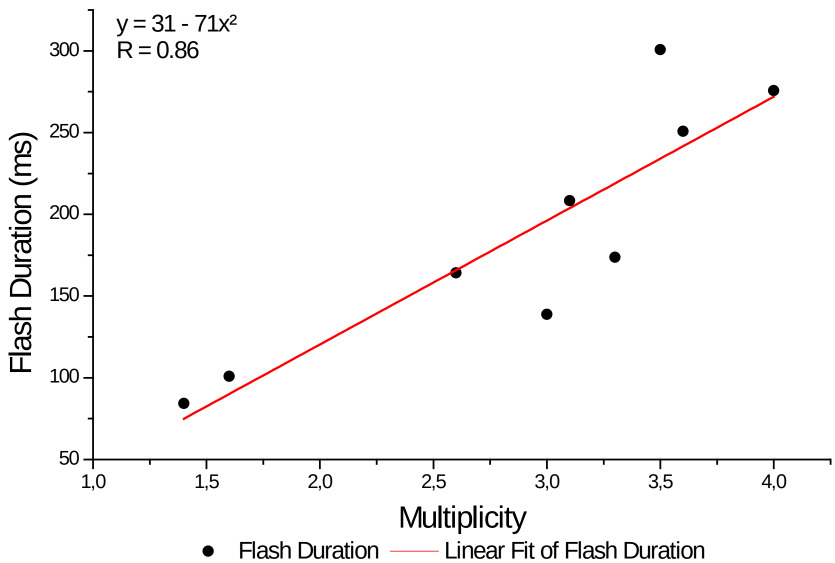

Figure 4 - Scatterplot showing the relation between the total flash duration and multiplicity (number of trokes per flash).

The explanation for the low multiplicity found in this case study could be explained by the linear relationship with the flash duration. If the flash duration is associated with the propagation of the leader inside the cloud, the size of the storm cell may have limited space to spread the developing positive leader. So, the formation of small clouds with small vertical development should be related to the occurrence of flashes with less return strokes (lower multiplicity) or even to a greater amount of single stroke flashes.

CONCLUSIONS

The paper presented a case study of the visible features of negative cloud-to-ground lightning flashes recorded on February 22nd, 2013, and their relationship with the thunderstorm characteristics. The observations were made with the help of the RAMMER network, which is formed by four high-speed cameras directed to observe the same region of the city of São José dos Campos. By comparing five thunderstorm days that had lightning filmed during the campaign in the summer of 2012/2013, one day showed significant differences in values of flash multiplicity and duration.

The five days of observation totaled 361 negative cloud-to-ground lightning flashes, among which 55 events were recorded by the cameras on February 22nd. The analysis of this day showed a low mean multiplicity (2.8) relative to the value found for the analysis of lightning considering the five thunderstorm days (4.3).

From the original sample referred to all five days, the Monte Carlo method was applied, producing 1,000 new samples of size equal to the sample of that day. It was concluded that the low multiplicity value was considered to be an anomaly when compared to the overall behavior of the other four thunderstorm days.

In order to find explanations for this anomaly, satellite images with infrared channel were analyzed. The data from weather radar also were used to compare them with data from high-speed cameras and the local lightning location system.

The satellite images showed that during the observation period the lightning flashes occurred throughout the development and dissipation of a single thunderstorm cell.

The CAPPI images of the cell at 5 km height showed that over 90% of lightning detected by the network occurred within the contour with reflectivity of at least 35 dBZ which is probably related to the horizontal extension of the negative charge region within the cloud. Using the bidirectional leader concept as a first approach, there should have a correlation between the area of 35 dBZ, the flash multiplicity and duration of lightning. The analysis showed the multiplicity tends to increase during the development of the cloud until its maturity, and after this stage the convective core begins to dissipate and consequently the multiplicity tends to decrease. Since the duration of the lightning flash is associated with the multiplicity, duration follows the same behavior multiplicity.

The main conclusion of this study is that the flashes that were recorded on February 22nd were related to a single small thunderstorm cell and that during its development it was isolated from other convective cells. The short horizontal development of this cell favored short duration flashes and, consequently, those either with only one return stroke or with low multiplicity.

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