Positive cloud-to-ground flashes and the initiation of upward lightning

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Abstract: Past research efforts have sought to characterize the type of triggering flashes and electric field environment prior to and during the initiation of upward leaders from tall objects in upward flashes. In São Paulo, Brazil and in South Dakota, USA simultaneous and collaborative campaigns were performed from 2012 to 2015 to study upward flashes from tall structures and their initiation. High-speed cameras, lightning mapping array (LMA), electric field sensors were used together with lightning location systems to understand the triggering mechanisms that initiate upward flashes. Results from this study and the role of positive cloud-to-ground flashes in the initiation of upward lightning will be presented.

Keywords: Upward flash, leader initiation, cloud-to-ground positive flash

1. INTRODUCTION

Upward lightning flashes initiates from tall structures (buildings, towers, wind turbines) and have been studied for almost one century. However, with the increasing number of tall buildings and towers, and the rapid expansion of wind power generation, the interest in this subject has grown recently. Upward flashes are not the most common type of flashes in nature (downward flashes are prevalent) but can pose a serious threat to skyscrapers, communication towers and wind turbines.

When the electric field over a tall structure intensifies, an upward propagating leader may initiate from the tip of the structure. This initiation is usually triggered by a nearby flash activity, but can also be self-initiated when the field intensification if high enough [1].

The innovative aspect of the present study is that it is based on a large dataset of 100 upward flashes (72 in Brazil and 28 in USA) observed with high-speed video cameras. It reports information that cannot be obtained from instrumented tower with current sensors and allows some general statistics on the parameters of upward leader initiation in upward flashes.

2. INSTRUMENTATION

2.1 HIGH-SPEED CAMERAS

Six different high-speed digital video cameras (Photron Fastcam 512 PCI, Phantom v7.1, v7.3, v310, v711 and Miro 4), have been used to record images of upward flashes in Sao Paulo (Brazil) and in South Dakota (USA) between 2011 and 2015. All video imagery was time-stamped to GPS with time-resolutions and exposure times ranging from 28.6 microseconds (35,000 frames per second) to 1 millisecond (1,000 frames per second). The minimum recording length of all the cameras was 1.8 seconds.

2.2 LIGHTNING LOCATION SYSTEMS

All upward flashes reported in this work had their initiation triggered by a previous discharge. Data from the lightning location systems (LLS) were used to determine: i) the classification of each previous discharge (cloud-to-ground or intracloud flashes); ii) their distance to the tower that initiated the upward flash; iii) the time interval between the previous discharge and the initiation of the upward flash, and iv) the polarity of the previous CG discharges. Further information about the performance of the LLS can be found in [2] and [3].

3. DATA AND METHODOLOGY

During summer seasons between 2011 and 2014 high-speed cameras were pointed toward several towers located in Rapid City, SD, USA and Sao Paulo, SP, Brazil. Rapid City is located in the northern High Plains of the United States and São Paulo city in the southeastern region of Brazil. Details about the towers and the characteristics of each region observed, the number of the storms and upward flashes observed are presented in Table 1. The relief contour of each region and the height of each tower observed in Sao Paulo (Brazil) and in South Dakota (USA) are shown in Figure 1.

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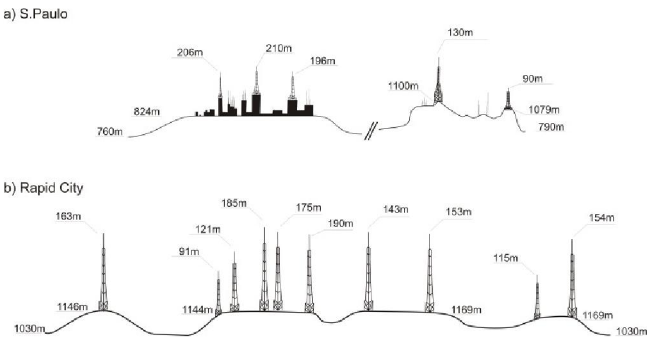

Figure 1 – Tower heights and relief profile for Sao Paulo (a) and Rapid City (b). The region depicted in the left side of the profile in Sao Paulo city was observed during one summer only.

Upward flashes start with an upward propagating positive or negative leader. The ones initiated by positive leaders are named negative upward flashes because they bring negative charge to ground. Positive upward flashes (rarely observed) are those initiated by negative upward leaders. All observed upward flashes in this work initiated with an upward propagating positive leader. One hundred high-speed video recordings (72 cases in Brazil and 28 cases in USA) of negative upward lightning flashes were analyzed. All upward flashes were triggered by another discharge, most of them positive.

TABLE 1 GENERAL CHARACTERISTICS OF UPWARD FLASHES OBSERVATIONS IN BRAZIL AND USA

	Rapid City, SD, USA	Sao Paulo, SP, Brazil
Location Characteristics		
Coordinates (lat, lon)	44.08 N; 103.23 W	23.55 S; 46.63 W
Altitude of surroundings, msl (m)	1030	760
Cloud base height (km)	2-4	1.2 – 3.4
Average flash density (flashes/km²/year)	3	15
Tower Characteristics		
Tower height range (m)	55 - 191	90 – 210
Number of towers producing upward flashes	8	6
Maximum distance between any pair of towers producing upward leaders during the same flash (km)	8	14
Distance range from cameras to towers (km)	2.5 – 9.0	1.0 – 8.5
Dataset Information		
Number of storms producing upward flashes	11	28
Number of upward flashes recorded	28	72
Average number of upward flashes per storm	2.5	2.6
Number of upward leader flashes involving more than one tower	16	8

4. RESULTS

The upward flashes described in this paper were either triggered by intracloud (IC) lightning or cloud-to-ground (CG) flashes. The discrimination of the triggering flash type (IC or CG flash) was based on video recordings and on data information from the LLS detection of the triggering discharges (Table 2).

TABLE 2 CLASSIFICATION OF TRIGGERING EVENTS

	Brazil	*USA*
Classification of upward flashes triggering events		
Number of upward flashes	72	28
Percentage triggered by CG flashes	84%	53%
Percentage triggered by IC flashes	6%	29%
Undetermined	10%	18%

In the majority of the upward flashes events (58 out of 69 in Brazil, 25 out of 28 in USA) it was possible to observe either horizontally propagating in-cloud brightness or a strong illumination of the sky preceding the initiation of the upward leader.

The LLS detected impulsive events recorded during triggering flashes were considered to be associated with the initiation of the upward flashes if their location was no more than 80 km away from the tower location and the reported time of their occurrence was no more than 1 second before or after the upward flash initiation.

Since an LLS can only detect impulsive events, the detection of the triggering flash occurs before or after the initiation of the upward leader, depending on when the impulsive part of the triggering flash takes place. A triggering flash, therefore, can have components that are not impulsive, (e.g., intracloud leader development), but which can trigger the initiation of an upward leader before a related impulsive flash component occurs (e.g., return stroke). Non-impulsive leader activity, which can frequently be seen by optical sensors, but not detected by an LLS, always preceded upward leader initiation. The distribution of the time interval between the detection of an impulsive event and the initiation of the upward leader(s) is presented in Figure 2. In this figure, a positive time interval means that a negative leader propagated over the tower and triggered the initiation of the upward leader before the occurrence of the impulsive and detectable process of the IC or CG discharge.

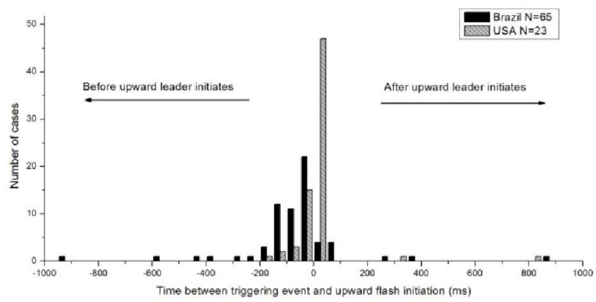

Figure 2 – Histogram of the time interval between the LLS detection of an impulsive event and the upward leader initiation.

In order to check if the longer time intervals shown in Figure 2 were related to more distant impulsive events during triggering flashes, a scatterplot of the time interval and the distance of the impulsive event to the tower (as reported by the LLS) was created (Figure 3). Note that, although the triggering leader does not propagate in a straight line nor has a constant speed, this plot suggests that the farther the distance of the impulsive event, the longer the interval between the impulsive event and the initiation of the upward leader(s).

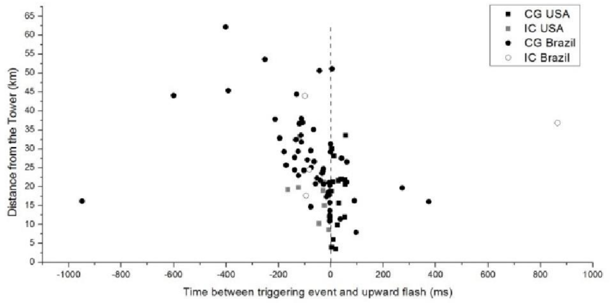

Figure 3 – Scatterplot of the distance of the triggering event and the time interval between the detection of the triggering event and the upward leader initiation.

An analysis of the impulsive event peak current estimated by the LLS was used to evaluate the intensity of these triggering flash components. Figure 4 shows the distribution of the estimated peak currents (Ip) for all impulsive events in Brazil and in USA.

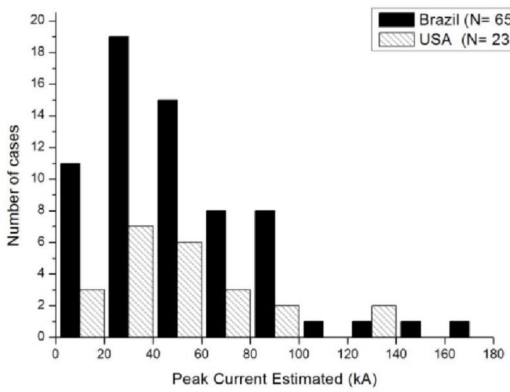

Figure 4 – Histogram of the estimated peak current of triggering events.

The scatterplots in Figure 5 shows individual Ip and distance from the tower where the upward flash initiated for both CG and IC cases. Note that a few high Ip values for IC cases are probably due to misclassification given by LLS. Reclassifying the cases of IC with Ip higher than 30 kA as +CG, the mean values of Ip in Brazil and USA are 50 and 63 kA, respectively. These averages are higher than the averages reported in previous studies on +CG characteristics (e.g. Ip mean value of 42.3 kA for Brazil [4]; and Ip mean value of 48.8 kA for USA [5]).

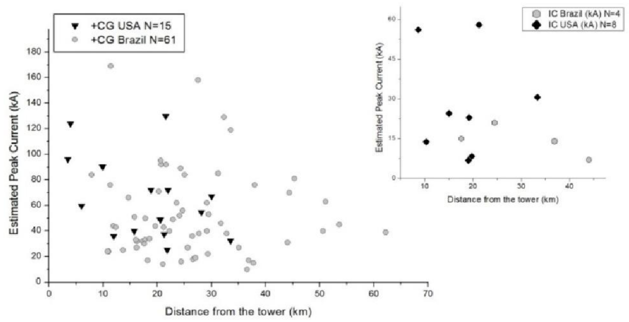

Figure 5 – Scatterplot of estimated Ip versus distance for CG and IC cases.

A single triggering flash was sometimes able to trigger upward leaders from several towers. In Brazil, 11% of the total upward flashes (8 out of 72) involved multiple towers. In USA the percentage of multiple upward leader flashes was 57% (16 out of 28). The higher percentage in USA can be explained if we consider that the region observed in USA had a higher density of towers. A maximum number of 5 towers producing simultaneous upward leaders was observed in USA.

5. CONCLUSIONS

In this paper, we analyzed highspeed video recordings of negative upward lightning flashes in Sao Paulo, Brazil (72 cases) and in South Dakota, USA (28 cases). The main contribution given by this work is summarized below.

All upward flashes recorded in Brazil and USA were triggered by a previous discharge. According to the LLS classification, most triggering flashes were positive CG flashes (84% in Brazil and 53% in USA). A negative leader (usually associated with the +CG flash) passing over the tower(s) was frequently seen in the high speed video recordings before the initiation of the upward leader. However, the impulsive and detected component of each triggering flash was detected either before (majority) or after the initiation of the upward leader(s). The time interval between the impulsive event and the initiation of the upward leader (usually lower than 200 ms) was longer for events occuring further from the towers.

One triggering component can sometimes initiate upward leader in several towers. The higher percentage of multiple tower initiation in USA can be explained if we consider that the region observed in USA has a higher density of towers.

6. ACKNOWLEGDEMENTS

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