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Key Points:

- Characteristics of upward flashes from high-speed video observations are presented and compared to studies of cloud-to-ground flashes
- All upward flashes in Brazil and in USA were triggered by another discharge, most of them positive CG flashes
- A negative leader passing over the tower was frequently seen in the high-speed video recordings before the initiation of the upward leader

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Upward lightning flashes characteristics from high-speed videos

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Abstract 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 CG flashes. A negative leader passing over the tower(s) was frequently seen in the high-speed video recordings before the initiation of the upward leader. One triggering component can sometimes initiate upward leader in several towers. Characteristics of leader branching, ICC pulses, recoil leader incidence, and interpulse interval are presented in this work. A comparison of the results is done for data obtained in Brazil and USA. The duration of ICC and the total flash duration are on average longer in Brazil than in USA. Only one fourth of all upward leaders are followed by any return strokes both in Brazil and USA, and the average number of return strokes following each upward leader is very low. The presence and duration of CC following return strokes in Brazil is more than two times larger than in USA. Several parameters of upward flashes were compared with similar ones from cloud-to-ground flashes.

1. Introduction

Upward lightning flashes initiate from tall structures (buildings, towers, and 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.

Several past studies on data from instrumented towers have reported statistics on parameters of upward flashes based on current sensor measurements [e.g., *Diendorfer et al.*, 2009; *Romero et al.*, 2013; *Hussein et al.*, 2004; *Guimarães et al.*, 2014]. Some studies have described the characteristics of a few (less than 15) upward flashes with high-speed video cameras [e.g., *Wang et al.*, 2008; *Mazur and Ruhnke*, 2011; *Flache et al.*, 2008; *Lu et al.*, 2009; *Jiang et al.*, 2014; *Warner*, 2012; *Warner et al.*, 2012]. The innovative aspect of the present study is that it is based on a large data set 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 (e.g., channel branching and channel luminosity) and allows, for the first time, some general statistics on basic parameters of upward flashes.

When the electric field over a tall structure intensifies, an upward propagating leader may initiate from the tip of the structure (Figure 1b). This initiation is usually triggered by a nearby flash activity and can also be self-initiated when the field intensification if high enough. Once the upward leader starts its propagation toward the cloud base an initial continuous current (ICC) starts to flow through the channel that is being formed (Figure 1c). This upward leader may or may not branch before reaching the cloud base. Pulses of luminosity in the channel usually occur indicating fluctuations in the current. These pulses are named ICC pulses (Figure 1e). After the channel luminosity (and current) decay (Figure 1f) and a period of no-luminosity interval (Figure 1g), one or more sequences of dart-leader-return-stroke may occur (Figure 1h). As in cloud-to-ground flashes the return stroke (RS) may be followed by a continuing current (CC), and as during the ICC phase, fluctuations in the luminosity of the continuing current (named M-components) may occur (Figure 2).

This paper will summarize the results of our observations of upward lightning flashes that were recorded using high-speed video cameras in correlation with data from lightning location systems in Brazil and the

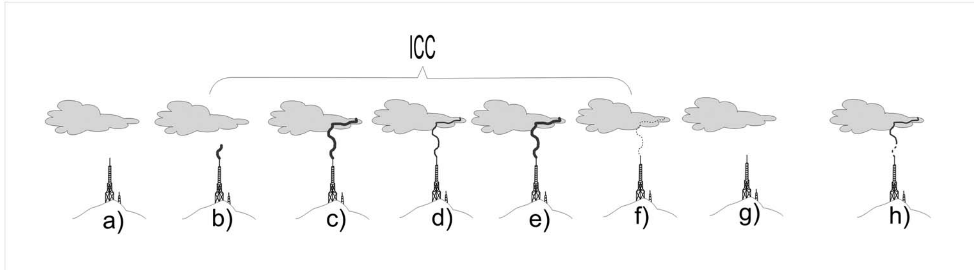

Figure 1. Upward flash stages: (a) previous activity IC or (b) CG flashes initiation of ICC; (c) complete channel up to the cloud; (d) luminosity decreases; (e) ICC pulses intensify the luminosity of the channel; (f) decay of the channel luminosity —ICC ends; (g) no current interval; and (h) a RS using the previous channel may occur.

United States. Our main objective will be to provide an up-to-date summary of the physical parameters of negative upward flashes.

2. Instrumentation

All analysis presented in this work were based on information provided by high-speed video recordings and by data from lightning location networks.

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 2014. All video imagery was time stamped to GPS with time resolutions and exposure times ranging from 28.6 μs (35,000 frames per second) to 1 ms (1000 frames per second). The minimum recording length of all the cameras was 1.8 s. See the works by *Saba et al.* [2006], *Schulz and Saba* [2009], and *Warner* [2012] for more details about the accuracy and use of high-speed camera technology for lightning observations.

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 the following: (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.

All recordings were obtained in geographical regions that were covered by lightning location systems (BrasilDat and Rindat in Brazil and the NLDN in the USA). Most (around 90%) estimated peak currents values were given by BrasilDat. Further information about the performance of the two LLS can be found in *Schulz et al.* [2005], *Cummins and Murphy* [2009], and *Naccarato and Pinto* [2009].

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

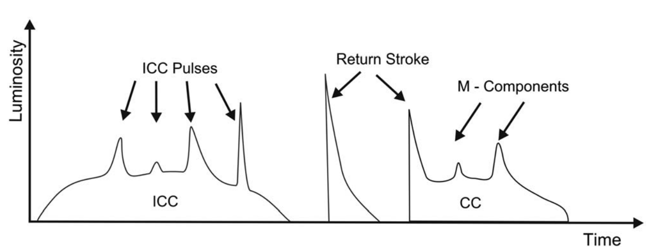

Figure 2. Schematic channel luminosity record for an upward initiated flash. The ICC is followed by two RS after a time interval of no current flow.

Table 1. General Characteristics of Upward Flashes Observations in Brazil and USA

	Rapid City, SD, USA	Sao Paulo, SP, Brazil
Location Characteristics		
Coordinates (latitude, longitude)	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/km^2/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
Data Set 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

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 3.

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.

Mazur [2002] and *Saba et al.* [2008] reported that the presence of recoil leaders, i.e., negative leader retracing branching channels that became cutoff, occurs only in positive polarity leader development. *Mazur and Ruhnke* [1993] also reports that positive upward flashes (initiated by upward negative leader) are never followed by return strokes. This information was used to identify the polarity of the upward leader and, consequently, the polarity of the upward flash. Although this polarity determination criterion would not work for bipolar upward flashes, their occurrence is very rare (only 3% of 652 upward flashes observed by *Zhou et al.* [2011]).

Occasionally, an upward flash may have several upward leaders initiated from different towers almost simultaneously (within hundreds of milliseconds); these cases will be classified as multiple upward leader

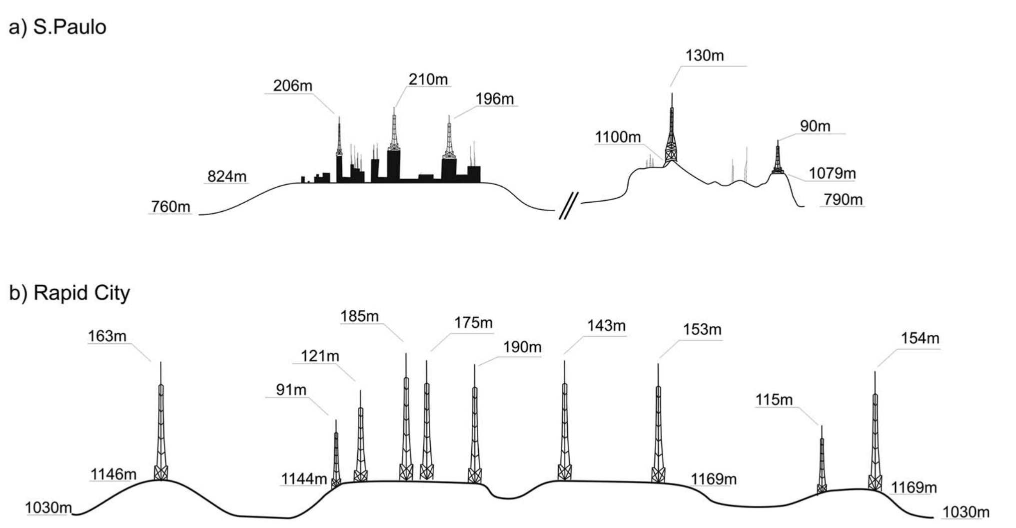

Figure 3. Tower heights and relief profile for (a) Sao Paulo and (b) Rapid City. The region depicted in the left side of the profile in Sao Paulo city was observed during one summer only.

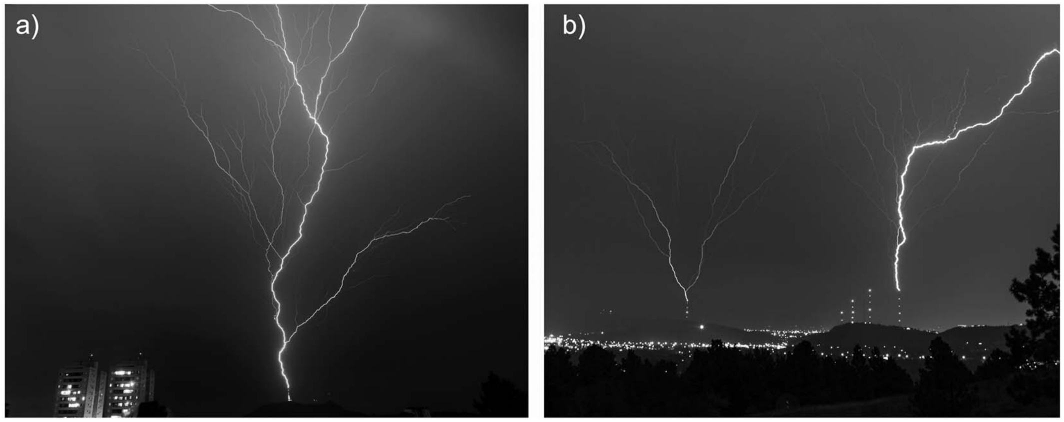

Figure 4. Example of upward flash from one tower in (a) Sao Paulo, Brazil (16 January 2014) and from multiple towers in (b) South Dakota, USA (5 August 2013).

flash (Figure 4). In cases of leaders starting from multiple towers, if recoil leaders are observed in one leader, or any return stroke is observed, then all leaders are assumed to have the same polarity. This assumption is based on the fact that all leader initiations responded to a common positive or negative triggering event.

Both in Brazil and in USA, in most cases it was possible to see the presence of recoil leaders during the upward propagation of the leader. For a few cases, where this was not possible, we checked if the upward leader was followed or not by return strokes.

In this work, only the characteristics of negative upward flashes will be described. Out of 76 high-speed video recordings of upward flashes in Brazil, 72 were confirmed by the above criteria as negative upward flashes. In USA, all 28 upward flashes recorded were of negative polarity.

Table 2. Summary

	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%
Leader Branching		
Number of leaders	75	62
Percentage of nonbranching leaders	40%	37%
Percentage of branched leaders	60%	63%
Percentage of branching at the tower tip	3%	18%
Initial Continuous Current		
Number of ICC	79	65
Percentage of ICC containing pulses	54%	51%
Number of ICC pulses	197	236
Average number of ICC pulses for all ICC cases	2.5	3.6
Average number of ICC pulses for cases of ICC with pulses	4.6	7.2
Return Stroke		
Number of leaders	79	65
Percentage of upward leaders followed by RS	24%	26%
Average return stroke multiplicity for leaders followed by RS	2.0	3.4
Average return stroke multiplicity for all leaders	0.5	0.9
Number of thunderstorms producing RS	6 out 28	4 out of 11
Continuing Current		
Number of RS followed by continuing current	39	57
Percentage of RS with some CC	90%	40%
Percentage of RS with long CC	26%	5%

For the analysis of some of the parameters described, we used measurements from all negative upward flashes (72 in Brazil and 28 in USA); however, for parameters that required better observational conditions, only a subset of the data set was used.

The number of ICC pulses and return strokes (return stroke multiplicity) will be determined for each upward leader; therefore, if a multiple upward leader flash occurs, the number of ICC pulses or return strokes is the number of ICC pulses or return strokes striking each tower. This criterion is also applied when a flash has a bifurcation right at the tip of the tower. It is observed that each leader emerging from the bifurcation at the tip of the tower behaves as if the other leader was not present. Therefore, in this case the number of ICC pulses and return strokes is also counted for each leader branch.

4. Results

The following sections will present how the upward flashes initiated, the characteristics of the upward leader, the duration of the initial continuous current (ICC) and the presence of pulses during each ICC, the presence and number of return strokes following each upward leader, the presence and duration of continuing current following return strokes, and finally, statistics on the total flash duration.

4.1. Upward Flash Initiation

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).

In the majority of the upward flashes events (58 out of 69 in Brazil and 25 out of 28 in USA) it was possible to observe either horizontally propagating in-cloud brightness or a strong illumination of the sky is 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 s 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). Nonimpulsive 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 5. 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.

In order to check if the longer time intervals shown in Figure 5 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 6). 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).

An analysis of the impulsive event peak current estimated by the LLS was used to evaluate the intensity of these triggering flash components. Figure 7 shows the distribution of the estimated peak currents (I_p) for all impulsive events in Brazil and in USA.

The scatterplots in Figure 8 shows individual I_p and distance from the tower where the upward flash initiated for both CG and IC cases. Note that a few high I_p values for IC cases are probably due to misclassification given by LLS. Reclassifying, the cases of IC with I_p higher than 30 kA as + CG, the mean values of I_p in Brazil and USA, are 50 and 63 kA, respectively. These averages are higher than the averages reported in previous studies on

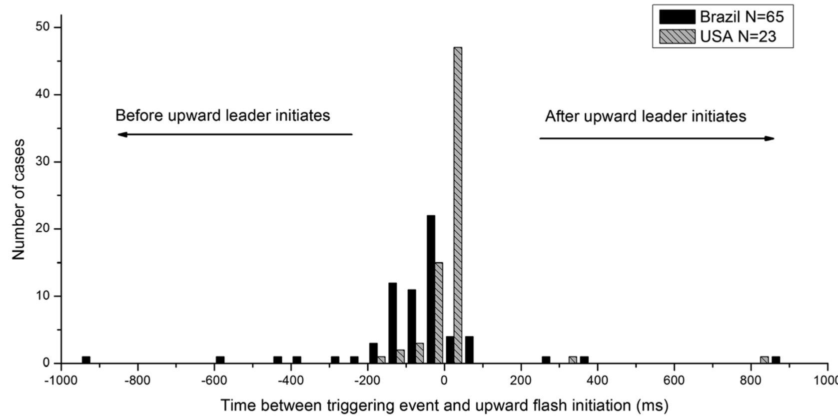

Figure 5. Histogram of the time interval between the LLS detection of an impulsive event and the upward leader initiation.

+CG characteristics (e.g., I_p mean value of 42.3 kA for Brazil [*Saba et al*., 2010] and I_p mean value of 48.8 kA for USA [*Fleenor et al*., 2009]).

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 five towers producing simultaneous upward leaders were observed in USA.

4.2. Upward Leader Characteristics

4.2.1. Leader Branching

An upward leader during its propagation toward the cloud base may branch or not. This branching sometimes occurs right at the tower tip (Figure 9). The statistics of leader branching is shown in Table 2. In USA, 11 (18%) of 62 leaders branched at the tip of the tower. In 8 of these 11 cases, other leaders also initiated from other towers.

The time distribution of time interval between the leader initiation and first branching (bifurcation) is shown in Figure 10a. Statistics on these values are presented in Table 3.

4.2.2. Time Interval Between the Initiation of the Upward Leader and the Occurrence of the First RL

As the positive propagates toward the cloud base its intensity usually diminishes. When this occurs, it is not uncommon to see the appearance of recoil leaders. The time interval distribution between the initiation of the upward leader and the occurrence of the first recoil leader (RL) is presented in Figure 10a.

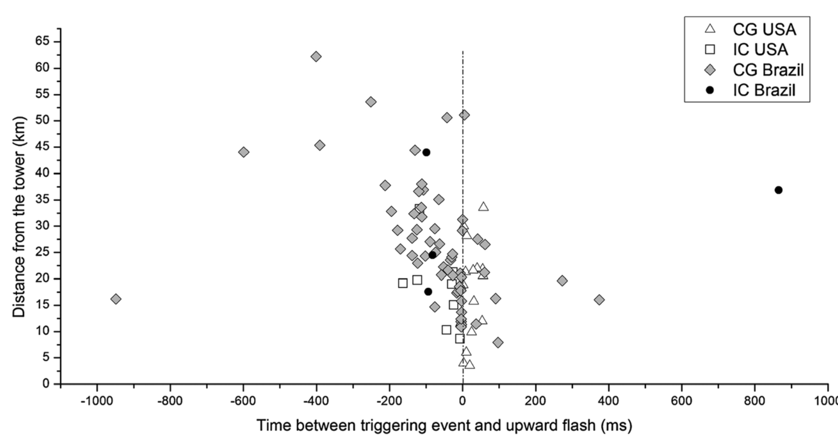

Figure 6. Scatterplot of the distance of the triggering event and the time interval between the LLS detection of the triggering event and the upward leader initiation.

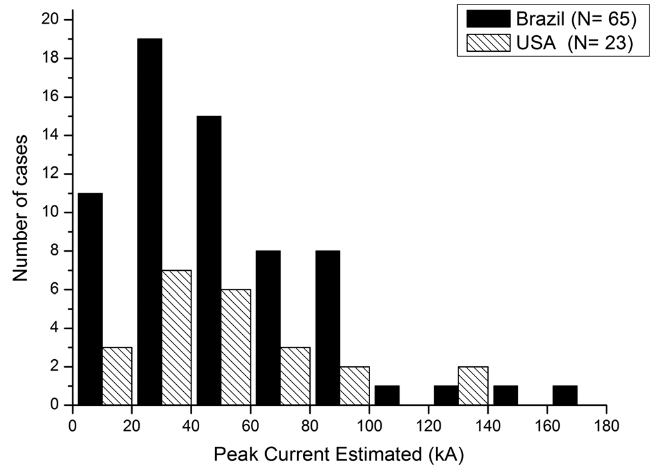

Figure 7. Histogram of the estimated peak current of triggering events.

When a leader bifurcates, it is observed that the luminosity of each branch is usually lower. This also seems to be a contributing factor to the appearance of RL. In fact we observe that the mean time interval value between leader initiation to first appearance of recoil leader is more than three times higher than the mean time interval value between the leader initiation to first bifurcation (Table 3).

4.3. Initial Continuous Current

The initial continuous current is the longest phase of an upward flash. Its long duration, as in continuing currents that follow some return strokes, may be responsible for most serious lightning damage associated with thermal effects.

4.3.1. ICC Duration

The duration of an ICC is determined by the time interval between the initiation of the upward leader and the cessation of the channel luminosity (Figure 2). The mean time duration values and the minimum and maximum values for ICC duration for Brazil and USA are shown in Table 4. The distribution of ICC duration is shown in Figure 11.

In Table 4 we also present of duration of continuing current that follows return stroke in negative CG for comparison. The comparison is done with CC from negative CG, because both CC of –CG and ICC of negative

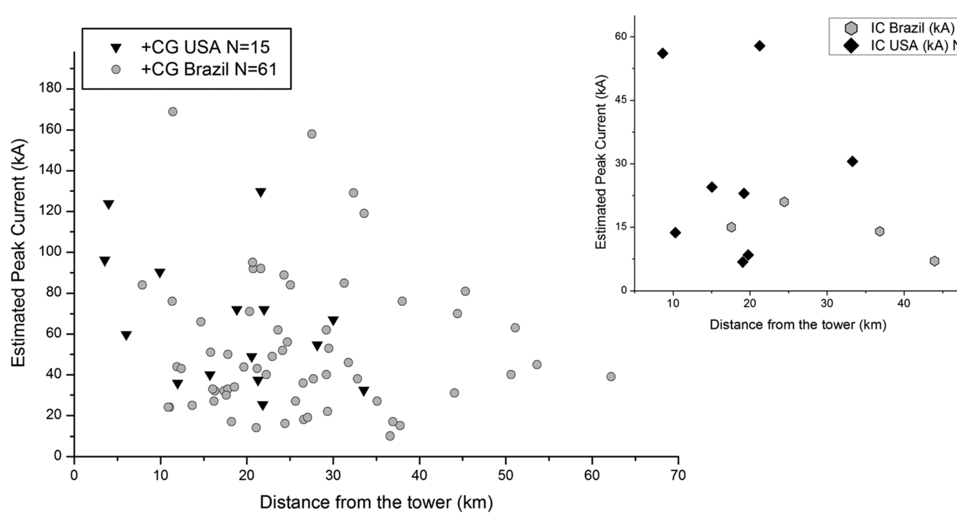

Figure 8. Scatterplot of estimated I_p versus distance for CG and IC cases.

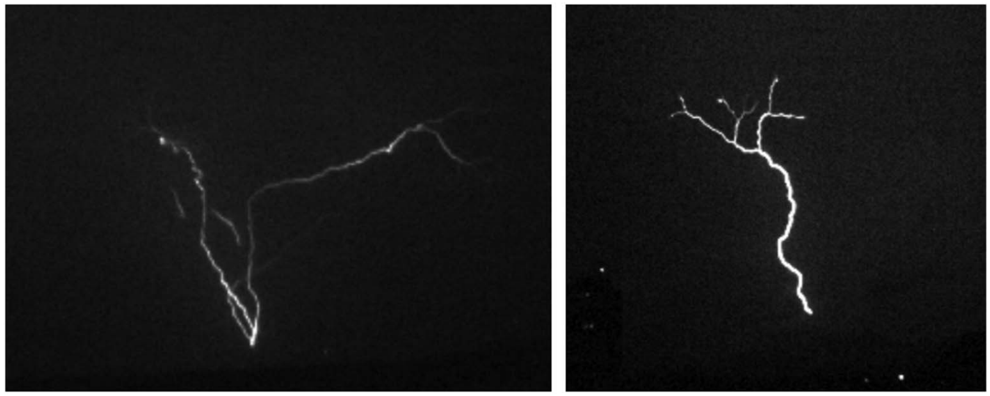

Figure 9. Leader branching occurring on the tower tip and before reaching the cloud base.

upward flashes depend on the propagation of a positive leader in the cloud. Note that the average ICC duration is much longer than the average CC duration (CC $\geq$ 3 ms), even if only long CC duration is considered (CC $>$ 40 ms).

4.3.2. ICC Pulses

ICC pulses are seen in video observations as an intensification of brightness in the main channel of the lightning channel (Figure 12a). They are produced by the downward propagation of the negative end of the RL along the luminous channel [*Mazur and Ruhnke*, 2011]. Only events that intensified the channel all the way to the tip of the tower were counted as ICC pulses. About half of all ICC contained ICC pulses in Brazil and in USA (Table 2). The average number of ICC pulses per ICC is similar to the average number of *M* components in negative CG flashes (5.5) reported by *Campos et al.* [2007].

The time interval between ICC pulses in Brazil is almost two times longer than in USA. In order to compare with the study done in Austria (based solely on current level measured at an instrumented tower by *Diendorfer et al.* [2009]), we recalculated the time interval without making distinction between ICC pulses and return strokes (which is only possible if a camera is available; e.g., Figure 12c). The resulting time interval was similar to what was reported by *Diendorfer et al.* [2009].

It is interesting to note that the time interval between ICC pulses in upward flashes is similar to the time interval between *M* components in negative CG flashes (Table 3).

4.4. Return Stroke Multiplicity

As mentioned before, the number of return strokes (return stroke multiplicity) in this work will be determined by the number of return strokes that follow each upward leader, that is, the number of strokes striking each tower.

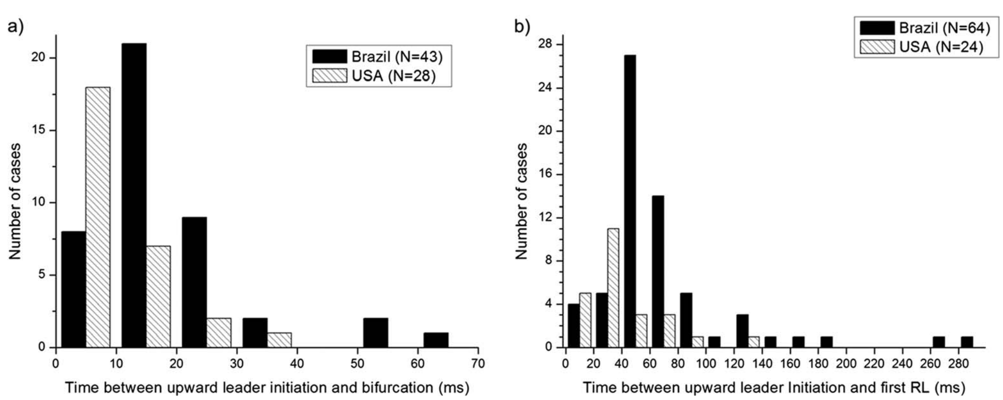

Figure 10. Distribution of (a) time interval between the initiation of the upward leader and the occurrence of the first RL and (b) between upward leader initiation and first leader bifurcation.

Table 3. Time Interval between Processes in Negative Upward Flashes and Negative CG Flashes

	Location	Sample	Mean (ms)	GM (ms)	Median (ms)	Minimum (ms)	Maximum (ms)
			Upward Flashes				
Time interval: Leader initiation to first bifurcation	Brazil	43	19.0	15.6	18	3.2	61.7
	USA	28	9.5	6.0	6.0	0.2	33
Time interval: Leader initiation to first RL	Brazil	64	70.6	55.1	56.8	1.2	281
	USA	24	39.7	31.0	31.8	6.6	134
			Time Interval Between				
ICC pulses	Brazil	154	34.5	19.8	20.7	0.2	227
	USA	204	16.3	10.6	11.0	0.2	142
RS	Brazil	20	54.3	40.7	39.3	3.5	114
	USA	41	16.3	13.2	11.6	3.2	53.7
ICC pulses and RS	Brazil	184	40.6	23.1	23.8	0.2	275
	USA	258	20.9	11.2	10.7	0.3	620
RS [*Diendorfer et al.* 2009]	Austria	476		17.3	18.6		
			Negative CG Flashes—Time Interval				
M component [*Campos et al.* 2007]	Brazil	289		11			
RS [*Saba et al.* 2006]	Brazil	608		61			

The percentage of upward leaders followed by return stroke is very similar, 24% (19 out of 79) for Brazil and 26% (17 out of 65) for USA (Table 2). The leaders containing return strokes occurred during a few number of thunderstorms (6 out 28 in Brazil and 4 out of 11 in USA).

The average multiplicity of return strokes is 2.0 in Brazil (total of 39 strokes in 19 upward leaders) and 3.4 in USA (total of 57 strokes in 17 leaders). If all upward leaders are considered, then the multiplicity drops to 0.5 in Brazil (total of 39 strokes in 79 upward leaders) and 0.9 in USA (total of 57 strokes in 65 leaders). Figure 13 shows a histogram of the number of strokes per leader for Brazil and USA.

It is interesting to note in Table 3 that the time interval between return strokes in upward flashes is much smaller in USA. Although they are longer than the time interval between ICC pulses, they are both shorter than the time interval between return strokes in −CG flashes.

In general, the interstroke time interval for upward flashes is notably shorter than the interstroke time interval in CG flashes. This is probably related to the fact that majority of upward flashes have leaders that branched before or when reaching cloud base. This branching multiplies the number of recoil leaders that reach the tower in a time interval, thus increasing the number of return strokes in a fixed time interval. In CG flashes, however, this is not observed.

Table 4. Statistics on ICC, CC and Total Flash Duration

	Location	Sample Size	AM	GM	Median	Minimum	Maximum
			ICC Duration (ms)				
ICC	Brazil	79	370	330	336	72	1143
	USA	65	233	174	195	10	616
			Duration of CC (ms)				
Upward flash	Brazil	35	60	41	21	4	571
	USA	23	19	11	10	3	101
−CG CC (≥3 ms)[a] [*Ballarotti et al.* 2012]	Brazil	2180	31	-	6	3	714
−CG CC (>40 ms)[b] [*Ballarotti et al.* 2012]	Brazil	304	173	-	137	40	714
			Flash Total Duration (ms)				
Upward flash	Brazil	72	427	372	430	86	1143
Upward flash	USA	28	365	308	363	22	682
Negative CG	Brazil	736	423	-	300		1430

[a]All values of CC duration are considered (assuming that they must last 3 ms or more).
[b]Only values of CC longer than 40 ms are considered (long CC).

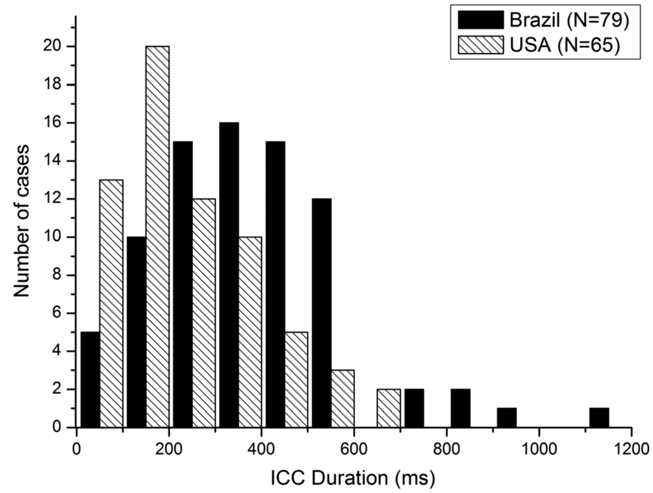

Figure 11. ICC duration distribution for USA and Brazil.

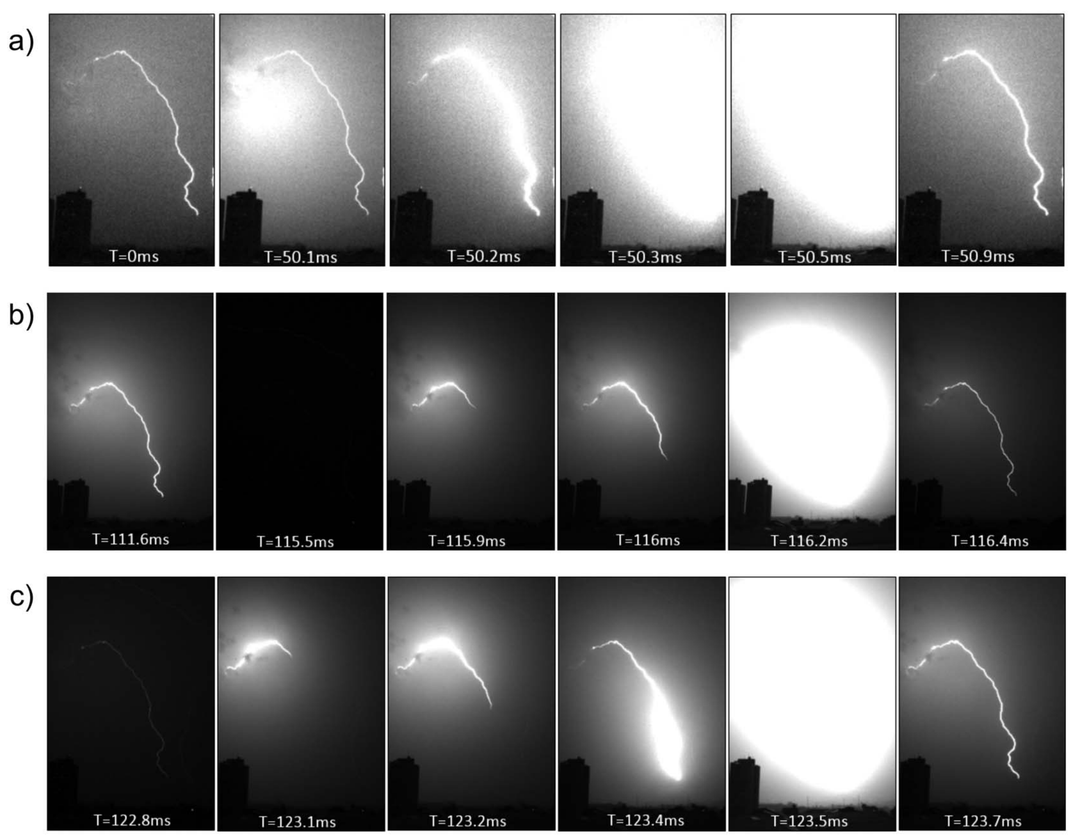

Figure 12. Sequence of images of (a) an ICC pulse, (b) a return stroke, and (c) an *M* component from video recording of upward flash (9 March 2013, 23:29:02,489). Note the faint luminosity of the channel before the occurrence of the ICC pulse and of the *M* component. Note also the complete absence of luminosity in the second frame before the initation of a dart leader in the third frame (Figure 12b).

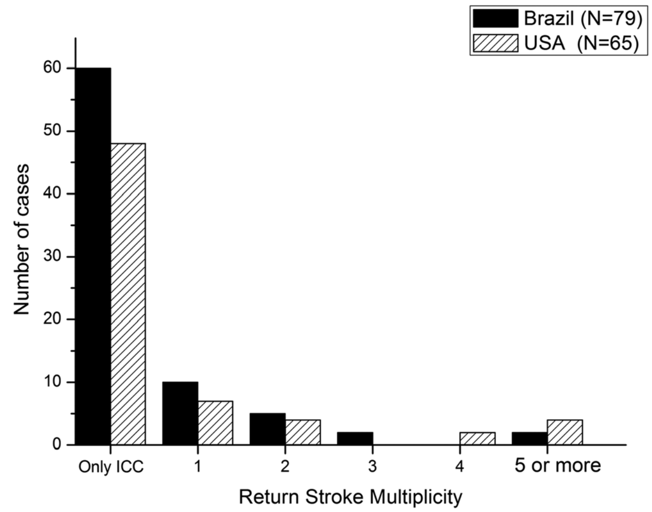

Figure 13. Histogram of the number of strokes per leader for Brazil and USA.

4.5. Continuing Current

4.5.1. Presence of CC

The percentages of return strokes followed by CC in upward flashes in Brazil are large, more than two times larger than in USA (Table 2). The percentage in USA is, however, very similar to what was found in Brazil [*Ballarotti et al.*, 2012] for cloud-to-ground negative flashes (47% containing CC and 7% containing long CC).

4.5.2. Duration of CC

The duration of CC is defined in this work and other past studies [*Saba et al.*, 2010; *Ballarotti et al.*, 2005] as the duration of the channel luminosity after the return stroke. As in these past studies, the minimum CC duration accepted value is 3 ms. This minimum duration is defined in order to avoid contamination from what might be just the tail on the return stroke current impulse. A summary of the results is shown in Table 4. Contrary to what was observed for the duration of ICC, the duration of CC in upward flashes is similar to what was observed for negative CG flashes.

4.6. Total Flash Duration

The total flash duration is defined as the time interval between the initiation of the upward leader and the cessation of the continuing current of the last return stroke. The histogram shown in Figure 14 presents the total flash distribution for Brazil and USA.

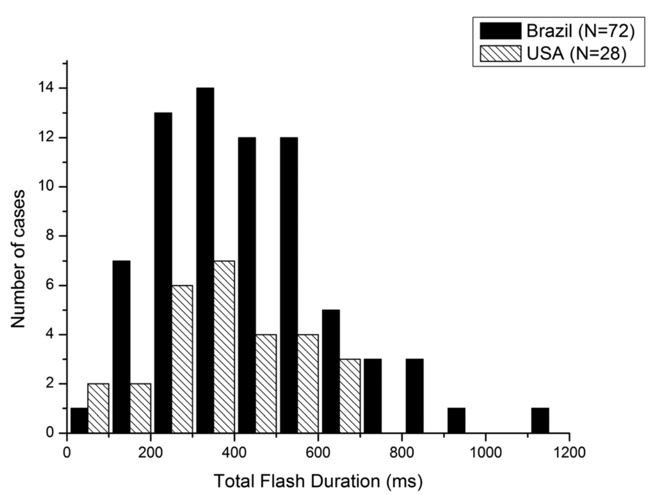

Figure 14. Total flash duration distribution.

The total flash duration of upward flashes is comparable to the duration of negative CG flashes (Table 4). Although upward flashes contain long ICC (not present in CG flashes), their return stroke multiplicity is very low if compared to −CG flashes (as reported before and shown in Table 2). Therefore, the absence of multiple return strokes is compensated by the long duration of ICC, resulting in a similar duration.

5. Summary and Discussion

In this paper, we analyzed high-speed 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 occurring 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.

The majority of upward propagating leaders (approximately 60%) branch before reaching the cloud base. They may also branch right at the tip of the tower (11 cases in USA and 2 in Brazil). When branching occurs at the tip of the tower, multiple tower initiation also generally occurs.

Recoil leaders usually appear when the luminosity of the upward leader diminishes. Leader bifurcation seems to be a contributing factor to the appearance of RL.

The average duration of ICC present in all upward flashes is much longer than the average CC duration present in CG flashes, even if only long CC duration (CC $>$ 40 ms) is considered. About half of all ICC contained ICC pulses in Brazil and in USA and the time interval between ICC pulses in Brazil is almost two times longer than in USA.

The time interval between ICC pulses and the average number of ICC pulses per ICC is similar to the time interval and average number of *M* components in negative CG flashes [*Campos et al*., 2007]. These facts, together with the similar appearance on the high-speed images (Figure 12b), leads us to consider ICC pulses and *M* components as similar or identical lightning processes in agreement with several other cases reported by *Wang et al.* [1999] and *Miki et al.* [2005].

Only one fourth of all upward leaders are followed by any return stroke both in Brazil and USA, and the average number of return strokes following each upward leader is very low, 0.5 in Brazil (total of 39 strokes in 79 upward leaders) and 0.9 in USA (total of 57 strokes in 65 leaders). If only leaders followed by RS are considered, the average is 2.0 and 3.4 for Brazil and USA, respectively.

In Austria, an average multiplicity of 4.4 RS per flash (excluding the ones without RS) was found [*Diendorfer et al*., 2009]. This result is similar to the multiplicity found by *Ballarotti et al.* [2012] for negative flashes. However, whereas the results obtained in Austria are based on current measurement only, the ones obtained in this study and by *Ballarotti et al.* [2012] are based solely on video recordings.

The presence of a long-duration current (ICC) at the beginning of upward flashes (absent in −CG flashes) may create favorable conditions (e.g., a highly ionized channel) to the occurrence of ICC pulses and not return strokes. Besides, when leader branches share a common part of the channel (the lower end close to tower), the impulsive RL in one branch will, when traveling toward the tower, traverse a luminous bottom part of the channel due to the current flow supplied by the other branch [*Miki et al*., 2005]. In this case, what could have been an RS turns out to be a ICC, according to the classification of ICC and RS.

In general, the interstroke time interval for upward flashes is notably smaller than the interstroke time interval in CG flashes. This is probably related to the fact that majority of upward flashes have leaders that branched before or when reaching cloud base. This branching multiplies the number of recoil leaders that reach the tower in a time interval, thus increasing the number of return stroke in a fixed time interval. In CG flashes, however, this does not happen.

The percentage of return strokes followed by CC in upward flashes in USA is very similar to what was found in Brazil for negative CG flashes (47% containing CC and 7% containing long CC). The presence and duration of CC following RS in Brazil is, however, much higher, more than two times larger than in USA.

The total flash duration of upward flashes is comparable to the duration of negative CG flashes. Although upward flashes contain long ICC (not present in CG flashes), their return stroke multiplicity is very low if compared to −CG. Therefore, the absence of multiple return strokes is compensated by the long duration of ICC, resulting in a similar duration.

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